ELEMENTS OF GEOLOGY

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PREFACE

This is an elementary textbook, not a manual or reference book. The authors have sought to give the student (1) an understanding of the general principles and processes of the science, (2) a few of its fundamental facts, (3) an interest in the subject, and especially (4) training in clear thinking. Many of the mere facts of the science will be forgotten presently by most students. The power and habit of reasoning logically and of thinking clearly will be of service to the student in meeting every problem of later life. The constant aim has accordingly been to make the text explanatory rather than merely descriptive, and to appeal to the judgment rather than to the memory. The book has been written with the belief that, while it is the duty of the teacher to develop in the student the power to reason, it is the business equally of the text. This has determined even the nature of the questions asked at the ends of most of the Chapters, and elsewhere. They are in general not questions the answers to which may be found in the text, but questions which the student may reason out for himself, provided the text has been read with understanding.

The book departs from current practice more or less in the arrangement of its material, and particularly in the omission of separate chapters on volcanoes and earthquakes. Though very interesting and from some standpoints important, volcanoes, and especially earthquakes, have been minor factors in the development of the earth, so much so as not to merit, in the opinion of the authors, the space commonly allotted to them in textbooks.

In the historical chapters "standard sections" have been omitted because in general they are of relatively local appli-

cation. It was desired to avoid, for example, the implication that mid-Ordovician was a time when limestone was being deposited in all seas, the sort of impression which the beginner is quite likely to get from the emphasis of so-called standard sections. Space has permitted only occasional reference to foreign geology. A synopsis of the groups of animals and plants is given because few beginning students of geology are sufficiently acquainted with them to be able to read intelligently an account of geological history. English names have been used for fossils wherever practicable, and the discussion of the life of the several periods has been shaped with the desire to afford the student a brief, simple picture of how life differentiated and developed gradually toward its present condition. Forms having little relation to this general theme are omitted, for in a brief course it is hardly possible to become acquainted with many specific kinds of fossils. But the larger facts of evolution can be understood. The historical maps are inserted, not with any intimation that they are correct in details, or that they will not need radical revision as time goes on, but because it is believed they will help the student to picture in its larger outlines the geography of the continent in past periods.

It is perhaps needless to say that work with the text should be supplemented by laboratory work with the common rocks and minerals, with typical fossils, with topographic and geologic maps, and by field excursions. No course in geology can accomplish what it should without these things.

We are greatly indebted to Professors T. C. Chamberlin and R. D. Salisbury of the University of Chicago, both of whom have read the manuscript, and have made many helpful criticisms and suggestions. Thanks are due also to Professor C. K. Leith of the University of Wisconsin, who has read certain of the Chapters, and to various friends who have kindly furnished photographs and helped in many other ways.

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ELEMENTS OF GEOLOGY

INTRODUCTION

The meaning and scope of geology. — Geology has to do with the history of the earth and of its inhabitants. Its field is so broad that for the sake of convenience and specialized study it has been divided into numerous branches. Geology is concerned with the different members of the solar system and with other heavenly bodies in so far as they yield evidence as to the origin of the earth, or affect the activities now in progress upon it. This division of the general subject is sometimes called *Astronomic Geology,* and is related closely to the science of Astronomy. The processes and agents at work changing the earth must be studied carefully by the geologist, for they are shaping the present chapter in the history of the earth, and an understanding of them affords also a key by which much of its earlier history, recorded in the rocks, may be read. This phase of the subject is *Dynamic Geology,* and it has common ground with the special science of Physiography or Physical Geography, with Meteorology, the science of the atmosphere, and with other sciences. The study of the remains and impressions of the plants and animals of past ages that are found in the rocks is *Paleontology;* it is really the historical side of Botany and Zoölogy. *Structural Geology* is concerned with the arrangement of the materials of the earth. That branch of geology which deals with minerals is *Mineralogy,* that which studies rocks is *Petrology;* both are connected closely with Chemistry. There are still other divisions of geology, but the ones mentioned are chief, and enough have been enumerated to show that geology is a very

broad science and that it is related closely to various sister sciences. The limits of these many branches are more or less artificial, and of necessity they overlap. A thoroughgoing study of any one of them requires more or less knowledge of some or all of the rest. Geology is indeed one great unified subject, and its branches are really leading phases of the subject, and not distinct divisions. Little or no attention is paid to them in this introductory survey of the science. In Part I the materials of the earth and their arrangement, together with the processes and agents which affect them, and the changes which these processes and agents are bringing about upon and within the earth, are discussed. This may be called *Physical Geology*. In Part II the history of the earth is outlined briefly in the light of the principles developed in the earlier chapters, and the progress of plant and animal life through past ages is sketched. This is *Historical Geology*.

Geologic processes and agents. — Throughout the earth incessant changes are going on, often so slowly, however, that centuries are required to make their effects visible. Rocks are broken, or are bent into folds, some of which appear on the surface as mountain ridges. These highlands are attacked in turn by wind, rain, ice, and other destructive agencies; their crumbled substance is carried off by streams, winds, and glaciers, only to be deposited elsewhere. Much of the detritus comes to rest finally in the oceans. There, other processes are at work to bind the loose grains into firm rocks, which may later be elevated above the sea and even be folded into more mountains.

The processes of change are most conspicuous where air, water, and rocks are in contact with one another. It is at the contact of air and sea that waves are made, and these in turn help to wear the land and to assort the sand and mud brought down by many streams. Where air and land meet, winds blow dust from one place to another, rains wash the soil, streams wear their channels, and mountain crags are riven by the expansion and contraction of the rocks and by the expansion

of water freezing in cracks. Beneath the surface, where the rocks are partly or wholly filled with water, changes are taking place slowly, as in a great chemical laboratory. Some parts of the rock are dissolved out, leaving a spongy, crumbling mass; other parts are cemented tightly by minerals left in the pores and cracks among the grains. Still deeper, where great pressure and heat are ever present, the rock is mashed, welded, squeezed into sheets, and molded like plastic clay. When such rock is resurrected through the wearing away of the cover, it is found so changed as to bear little resemblance to its original state.

The many processes of change may be grouped under four general headings. They are *diastrophism, vulcanism, metamorphism,* and *gradation.* (1) Diastrophism includes all movements of the earth's crust of whatever sort. Some are extremely slow and continue for long periods, while others are rapid and of brief duration. Some affect vast areas, and others are local. (2) Vulcanism comprises all processes by which lava and other volcanic products are forced to the surface from below, and by which lava is moved from lower to higher levels, even though it does not reach the surface. (3) The processes by which rocks are changed, whether that change results in decay or in consolidation, are included under metamorphism. (4) Gradation covers all processes which tend to reduce the irregularities of the solid part of the earth. An uneven surface may be made level by wearing down the high places, or by building up the low ones, and so gradational processes are divided into two classes. Those which seek to accomplish their end by leveling down the surface are called *degradational processes,* in contrast to those which tend to level it up, called *aggradational processes.* Both phases of gradational work are done by the atmosphere, underground waters, streams, glaciers, and by the waves and currents of the ocean and of lakes and seas. These processes and agents are discussed in subsequent Chapters.

PART I

PHYSICAL GEOLOGY

CHAPTER I

THE COMPOSITION OF THE EARTH

THE GREAT DIVISIONS OF THE EARTH

THE great divisions of the earth are the *atmosphere* or air, the *hydrosphere* or water portion, and the *lithosphere* or solid part (Fig. 1).

The atmosphere. — The atmosphere is a mixture of several gases. While nitrogen predominates, the three most important things in the atmosphere, geologically, are oxygen, carbon dioxide, and water vapor. They combine chemically with many substances of the lithosphere to form new compounds, and are especially important in decomposing surface rocks (p. 103). The condensation of the water vapor leads to the precipitation of rain or snow, and makes possible the work of running water and of ice. The work of the atmosphere in conditioning the rainfall is perhaps its greatest function, geologically. So far as mere volume is concerned, however, these gases are of minor importance. The water vapor, regarded frequently, like dust, as a foreign substance in the air, rather than a constituent of it, varies greatly in amount at different times and places. The carbon dioxide makes about .03 per cent and the oxygen about 21 per cent of the air, or approximately one fifth by volume. The remaining four fifths consists chiefly of nitrogen, an inactive gas chemically, whose importance geologically is confined largely to its mechanical effects.

The air when in motion performs mechanical work of great importance, especially in dry regions, transporting dust and sand, often for great distances, and wearing exposed rock surfaces (pp. 86–91). Wind-formed waves bring about important changes along ocean coasts and lake shores. The

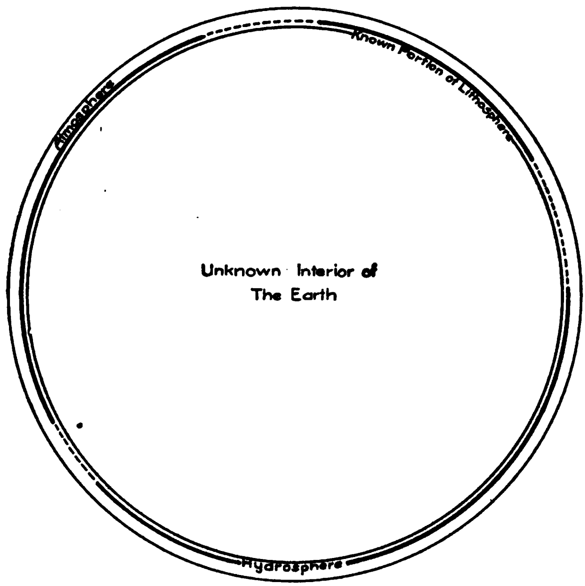


Fig. 1.—Diagram showing the general relations of the lithosphere, hydrosphere, and lower atmosphere.

atmosphere also acts as a blanket, protecting the rest of the earth from the fierce heat of the sun and preventing it from cooling off rapidly by radiation of heat. Winds distribute heat and tend to equalize temperatures.

Although the atmosphere is known to extend more than one hundred miles above sea level and probably continues very much higher, yet three fourths of the air lies below the tops of the highest mountains, and its geological activity is confined largely to its bottom portion, where it is in contact with the land and the water.

The hydrosphere. — The hydrosphere includes all the waters of the earth, — the oceans, seas, lakes, streams, and the water underground.

The oceans occupy nearly three fourths of the earth's surface, and contain water sufficient to cover the solid part of the earth nearly two miles deep, were the latter a perfect sphere. The oceans are all connected. If the level of the water in one is changed, all are affected. Streams wear the rocks over and against which they flow, and move loose material to lower levels, — much of it to the sea. Together with material worn by waves from the shore, or brought to the sea by other agents, the stream-borne waste of the land is spread out on the floor of the ocean as layers of sediment. The general effect of the work of the hydrosphere is therefore to wear down the surface of the land, and to build up the bottom of the ocean. The work of the waters beneath the surface of the land is chiefly chemical. Near the surface the general result is to bring about the decomposition of the rocks; at greater depths, the general effect is to strengthen them by depositing material in their pores and cracks.

FIG. 2. — Rock containing several kinds of fossils. (Photograph by Jessup.)

In the waters of the hydrosphere the same gases which make the air are dissolved, together with many solid substances. Common salt is dissolved in greatest abundance in the ocean, but the lime carbonate (p. 22) and silica (p. 19) in solution

are more important from the geological standpoint, since they are used by various forms of ocean life for the construction of their shells. The shells of marine organisms have frequently been embedded in the sediments derived from the land, and their remains or the impressions they made (*fossils*, Fig. 2) constitute an important, though imperfect, record of the life which existed at the time and place the sediments were accumulated.

The lithosphere. — The lithosphere, as the name implies, is composed of *rock* so far as known; it is the solid portion of the earth. As the science of geology deals very largely with rocks in one aspect or another, it is essential to study them and their arrangement in some detail.

The Materials of the Lithosphere

The mantle rock. — Loose, earthy material covers most of the land. When capable of supporting plant life, this is called *soil.* The earthy matter of soil is usually mixed with partly decayed vegetable matter, and then is often dark-colored, even black. Soils are generally composed of sandy, clayey, or limy particles, or of combinations of these in any proportion. In excavations for cellars, in railroad cuts, or in other exposures, it may often be seen that the soil gives place below to material which, though loose, is commonly coarser, more compact, and of different color. This is the *sub-*

Fig. 3. — Decaying granite and resulting rock waste. The granite is cut by a dike (p. 49). Southeastern Wyoming.

soil. The soil and subsoil have been called *mantle rock,* since they form a covering or mantle for the underlying rock, which is usually solid. Since the loose mantle rock is formed by the decay and breaking up of solid rock, it is also called *rock waste* (Fig. 3). Soil which remains above the solid rock from which it was derived is *residual soil,* in contrast to *transported soil,* which has been brought from its place of origin to its present situation by some of the agents which transport materials on the surface of the earth. Such soils when deposited by rivers are *alluvial soils,* and when accumulated by the wind, *eolian soils.* Much of the mantle rock of Canada and of the northern part of the United States was brought to its present position by the continental glaciers which once covered the region. This ice-transported material is called *drift.* The mantle rock ranges in thickness from inches to scores and, in exceptional cases, hundreds of feet.

FIG. 4. — Igneous rock. El Capitan, Yosemite Valley.

Classes of rocks. — Any considerable amount of mineral matter that has been brought together by natural means constitutes rock. A rock may contain material of one kind, or of several kinds, and may be loose, like sand, or solid, like granite. Popularly, one does not speak of sand or clay as rock, but thinks only of the solid rocks as such.

Although solid rocks are exposed only occasionally in the interior of the United States, as in quarries, mines, along the

FIG. 5.—Horizontal stratified rocks and bedding planes.

courses of certain streams, and in a few other situations, they *outcrop* (come to the surface) over large areas in eastern

FIG. 6.—Metamorphic rock. Contorted gneiss. Ontario, Canada. (Young, *Can. Geol. Surv.*)

Canada, among the western mountains, and elsewhere. They are found to differ among themselves in many ways. Their particles are of different kinds, sizes, and shapes; some of them are held together weakly, others firmly. Some rocks are arranged in distinct layers, while others are not. Since these and other differences are largely the result of the different ways in which the rocks were formed, they have been classified in the first instance on the basis of origin. Rocks formed by the solidification of lavas are *Igneous Rocks* (Fig. 4). Rocks formed by the consolidation of sediments are *Sedimentary Rocks.* Because the latter are usually arranged in layers or strata, they are often called *Stratified Rocks* (Fig. 5). If the character of an igneous or a sedimentary rock is radically altered, it becomes a *Metamorphic Rock* (Fig. 6). The more common rocks, and the minerals of which they are composed, are discussed below.

MINERALS

The igneous rock shown in Figure 7 is made up of many angular particles of several distinct kinds, each of which has its own constant characteristics. These particles can be separated, and, when treated in the proper manner, may be divided chemically into simpler things. Some of them, for example, may be divided into oxygen and silicon. Although chemists have been working with oxygen and silicon since their discovery, it has been impossible to get any still simpler things from them. They are accordingly called *chemical elements.* While some 70 elements are found in rocks, only 8 are important quantitatively. These are, in the order of abundance: oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K). The first two make up three fourths of the earth's crust; the eight, 98.95 per cent. The oxygen unites with the other seven elements to form the following *oxides:* silica (SiO_2), alumina (Al_2O_3), the iron oxides (FeO, Fe_2O_3, and Fe_3O^4), lime (CaO),

magnesia (MgO), soda (Na_2O), and potash (K_2O). The union of silica with the other oxides named, forms *silicates.* In similar manner, very many other combinations of elements, both simple and complex, occur in nature. The few elements which exist free as constituents of rocks, together with many definite compounds of elements which naturally take the solid form, are *minerals.* Ice is truly a mineral in this sense, but is not popularly so considered. Thus combinations of elements give rise to minerals, and aggregations of minerals form rocks.

When studied by themselves in larger pieces, minerals are found to have certain definite characteristics in addition to their nearly constant chemical composition. When formed under favorable conditions, most of them assume geometrical forms that are constant for each mineral. Common salt, for example, forms cubes. The form of any given crystal is determined by its internal structure, probably by the arrangement of the particles (*molecules*) of which it is composed. Even though the external form be marred or destroyed, this internal crystalline structure remains the same for each kind of mineral, and may be observed with the aid of a microscope in even the most irregular pieces of the substance.

Other convenient differences which may be used to tell one mineral from another are found in their color, manner of breaking, hardness, and luster. Some minerals break with a shelly fracture, like glass; others leave ragged surfaces, while many split more or less perfectly along certain planes, and thus leave shiny, flat surfaces. This relatively easy splitting in certain planes is called *cleavage.* It is one of the most distinctive features of many minerals.

Of the more than 800 varieties of minerals that have been named and classified, fewer than 50 are important either geologically or commercially, while about 8 make nearly all of the common rocks. Most of the metals are derived from a few more.

Quartz [1] (silica, SiO_2), familiar as the chief constituent of sand, is generally light-colored and glassy in appearance. When pure it is transparent, but various impurities give it different colors and special names. Quartz sometimes forms crystals, usually six-sided prisms capped with pyramids. In most rocks, it occurs as grains without definite shape. It is a very stable compound and is the hardest of the common minerals. Quartz will scratch glass and cannot be scratched with a knife. The cleavage of quartz is very poor; indeed, for all practical purposes, it may be regarded as without cleavage. It has a glasslike fracture, which is often a great help in distinguishing it in igneous rocks. Igneous rocks decay when exposed to the weather, and the loose products make mantle rock. In this process the more complex minerals are broken up, their elements entering into new and simpler combinations; but the quartz remains unaltered. This loose material may then be washed or blown away, the hard quartz particles becoming efficient agents in wearing the rock surfaces with which they come in contact.

Feldspars. — There are several kinds of feldspar, composed of silica and alumina, together with potassium, calcium, or sodium. The most common variety is *orthoclase* ($KAlSi_3O_8$), or potash feldspar, in which potassium is the distinguishing constituent. Feldspar is not quite so hard as quartz, but too hard to be scratched readily with a knife. The color of feldspar is variable, pale yellow, pink, and especially white and red varieties being common. The general color of many igneous rocks is determined by that of their feldspars. The excellent cleavage of feldspar leaves flat, glistening faces, which often afford the readiest means of distinguishing feldspar from quartz in rock. Feldspars are important constituents of most igneous rocks. Certain clays result from their rather ready decomposition.

Augite is a silicate of lime, magnesia, iron, and alumina. It is dark green or black in color, and crystallizes in oblique rhombic prisms. Augite crystals are short and stubby.

Hornblende is very similar to augite in chemical composition. Since the two minerals are also much alike in color and hardness, they are easily confused, and when they occur in small grains are often not distinguishable. Hornblende has two perfect cleavages, the surfaces meeting at angles of 125° and 55°, while in augite the cleavage planes meet nearly at right angles. This difference helps

[1] It is hardly necessary to say that the study and identification of actual specimens of minerals and rocks are absolutely essential to an understanding of them.

greatly in distinguishing the minerals when they occur in large crystals.

Mica is a complex silicate, and may be identified readily by the fact that it is the only common mineral that splits or cleaves into very thin (paperlike), elastic leaves. It is soft, and ranges in color from white to green and black. A light-colored variety of mica, called *muscovite*, a silicate of alumina and potash, is often used (under the name of isinglass) in stove doors and lanterns. A dark-colored variety, an iron-magnesia-silica compound, is called *biotite*. Hornblende, augite, and biotite are all iron-magnesia-silica compounds, and are known as *ferromagnesian* minerals.

Calcite (calcium carbonate, $CaCO_3$) is the principal constituent of limestone. It is scratched easily with a knife, and effervesces when touched with acid; by these tests it may be distinguished readily from feldspar, which it frequently resembles in general appearance. Calcite cleaves readily along three planes, so arranged as to make a rhombic pattern.

Gypsum (hydrous calcium sulphate, $CaSO_4 + 2\ H_2O$) is a white mineral, softer than calcite. It usually occurs in masses of small grains or fibers in which the crystal form is not visible, and is frequently stained brown or gray by the impurities it contains.

Olivine (a silicate of magnesia and iron) is a hard, glassy mineral, which may often be recognized by its grass-green or bottle-green color. It rarely forms good crystals in rocks, but occurs as grains and small masses without definite shape. The fracture is uneven. Olivine is rarely found in the presence of quartz.

Kaolin (a hydrous silicate of alumina) forms the basis of clay. It is very soft, and the individual particles are not visible. Pure kaolin is white and is known as "porcelain clay" because of its use in the manufacture of chinaware.

Hematite (iron oxide, Fe_2O_3) is steel-gray and hard when in the pure crystalline form, but soft, red varieties are common, and constitute the most important sources of iron ore in the Lake Superior district, at Birmingham, Alabama, and in many other places. This mineral occurs in many igneous rocks and is the red coloring matter of many soils and of bricks. It gives a red streak when rubbed with a harder surface, a fact by which it may be distinguished from other iron minerals.

Magnetite (iron oxide, Fe_3O_4) is black, and acts as a magnet. Its crystals are often cubes or double pyramids. Like hematite, it is an important ore of iron. It gives a black streak.

Limonite (hydrous iron oxide, $2\ Fe_2O_3 + 3\ H_2O$) is often called brown hematite. It is found frequently in marshes,

and is then also called bog iron ore. It gives a yellowish brown streak.

Of the minerals described above, quartz, feldspar, hornblende, augite, and mica make up the bulk of most igneous rocks. Few igneous rocks have a very large amount of any other mineral.

IGNEOUS ROCKS

As noted above, igneous rocks are the product of the consolidation of lavas. The character of an igneous rock is determined by (1) the chemical composition of the parent lava, and (2) the conditions under which that lava solidified.

FIG. 7.—Granite, about ¾ natural size. The light parts represent crystals of two kinds of minerals, and the dark spots represent crystals of other minerals. (Photograph by Baker.)

The kinds and proportions of chemical elements in a lava determine the kinds of minerals and their relative abundance in the rocks derived from it. Under different conditions of solidification, lava of a given chemical composition produces rocks of very different appearance. The mineral grains, for ex-

ample, may be large and easily distinguished (Fig. 7), or minute and unrecognizable. They may be of the same size, or of very unequal sizes (Fig. 8). These are matters of *texture*, rock texture having to do with the size, shape, and arrangement of the particles of a rock.

FIG. 8. — Porphyritic texture. About 3/8 natural size. (Photograph by Baker.)

Chemical classes of igneous rocks. — Those which contain a large proportion of silica (more than 65 per cent) are called *acidic rocks*, because silica is an acid-forming oxide (uniting with water to form silicic acid). Of the other leading oxides (p. 19) none commonly form acids. Similarly, those igneous rocks which contain much less silica (less than 55 per cent) and a larger proportion of the bases (lime, soda, magnesia, potash, etc.) are called *basic rocks*. Most acidic rocks are light-colored if crystalline, while basic rocks are commonly dark-colored. An *intermediate* or *neutral* group is sometimes recognized, including rocks that contain 55 to 65 per cent of silica.

Factors influencing the physical character of igneous rocks. — The circumstances under which lavas solidify vary greatly, and many factors influence the texture of igneous rocks. Among the leading ones are (1) the rate at which the lava cools, (2) the fluidity of the lava, and (3) the pressure under which it consolidates. The texture is influenced also by (4) the chemical composition of the lava.

(1) Lava is liquid rock, a solution in which certain minerals are dissolved in others. The high temperature of the lava appears to make it possible for the minerals to form a mutual solution. As lava cools, the point of saturation of some mineral present is reached, and it begins to take the solid form. The molecules of this mineral tend to collect and arrange themselves in regular order, building up crystals having a definite geometrical form. As cooling proceeds, the point of saturation of other minerals is reached, and crystals of other kinds begin to form. With continued cooling, the entire mass may become crystalline. Lava is probably never so fluid as water, and is commonly rather stiff (viscous). It clearly requires some time for molecules scattered throughout such a liquid to come together and form crystals. Slow, regular cooling therefore favors the development of large crystals. The resulting coarse-grained rocks are sometimes called *granitoids* (granitelike rocks). If cooling is rapid, the mass is likely to become solid before crystals have formed, or while they are still very minute. In the former case the rocks may

FIG. 9. — Obsidian, or natural glass. Shows the glassy luster and fracture. About ½ natural size. (Photograph by Baker.)

have the structure and luster of glass, and so are called *glassy rocks* (Fig. 9). When composed of very small crystals, the rock may have a dense, stony appearance, rather than a glassy luster. If, after certain minerals have crystallized out, the still liquid mass in which they float be cooled suddenly, a rock may result which is partly glassy or stony and partly crystalline (Fig. 8).

The rate of cooling, then, is a chief factor in the crystallization of igneous rocks. The rate is influenced by several conditions, of which the following are chief. (*a*) Large bodies of lava cool less rapidly than small ones. (*b*) Masses deep within the earth's crust cool more slowly than those at or near the surface. (*c*) The rate at which a body of lava cools is affected also by its shape. Thus a globular mass containing the same quantity as a thin sheet would cool far less rapidly. (What combination of these conditions would most favor the formation of coarse-grained rocks? Fine-grained?)

(2) The more fluid the lava, the easier and the farther may the molecules move, and the larger, other things being equal, may crystals grow. The mobility of the lava is determined largely by its temperature and composition, but partly by the amount of water vapor it contains, and to less extent by the presence of other volatile substances, such as carbon dioxide and fluorine. In addition to hindering the lava from becoming stiffly viscous, (*a*) the waters, etc., lower the temperature at which solidification occurs and so prolong the period of crystal growth, and (*b*) some common minerals do not form save in their presence. These substances, especially water, influence the process of crystallization so greatly that they are appropriately called *mineralizers*. That many lavas contain large quantities of water vapor is familiarly illustrated by the heavy rains which frequently attend volcanic eruptions, due to the condensation of escaping steam.

(3) The *direct* effect of pressure upon texture is probably not great. Most rocks contract on becoming solid, and, were other things equal, lava would therefore solidify more

quickly under pressure than otherwise. Accordingly, pressure tends to oppose slow crystallization and the development of coarse textures.

Indirectly, pressure affects texture greatly through its influence upon the gases and vapors included in the lava. As lava rises in the pipe or chimney which leads downward from the crater of a volcano, the weight of the overlying column of lava becomes less. This relief of pressure is likely to permit the explosive expansion of the steam, by which the lava is sometimes blown into fine bits and hurled high into the air. Very fine material was thrown to an estimated elevation of some 17 miles during the great eruption of Krakatoa (near Java) in 1883. Lava blocks a number of feet in diameter and weighing tons are also sometimes ejected, together with much material of intermediate size. In other cases the lava, possibly because not so heavily charged with steam, flows quietly from the volcanic vent.

As the lava at and near the surface of a flow solidifies, the gases expand readily without violent explosion, and the many steam bubbles frequently give the rock an open, spongy texture (Fig. 11). Since it cooled promptly, such material is often glassy. If the lava becomes solid under great pressure, as at the bottom of a thick flow or when intruded into the rocks deep below the surface, the included gases cannot expand freely, and the resulting rock has a compact texture. Cooling very slowly, such rock is apt also to be coarsely crystalline. The gases may be confined by even a thin covering which is relatively impervious to them, a solid texture resulting.

(4) It has already been pointed out that the chemical composition of lava determines the kinds and proportions of minerals in the rock formed from it. It may now be noted that this influences the texture of the rock, for different minerals form crystals of different shapes, so far as their interference with one another while growing will permit. Furthermore, lavas poor in silica, and particularly those rich in iron and magnesia, retain their fluidity to much lower temperatures

than do those containing much silica. Hence the former lavas may produce coarse-grained rocks under conditions where the latter would give fine-grained ones.

We are now prepared to describe a few of the more important igneous rocks. The different kinds grade into each other without hard and fast lines. [1]

Distinctly grained rocks. — These rocks have a solid texture, are wholly crystalline, and the grains can be distinguished with the unaided eye. The grains may be of uniform size (large, medium, or small), or large crystals may be scattered through a ground mass of smaller ones. In the latter case, the rock is called *porphyry*, and is said to have a *porphyritic texture*. These terms are applied also to rocks in which distinct crystals are scattered through a glassy or stony ground mass (Fig. 8). One way in which porphyritic texture develops has been explained (p. 26). The distinctly grained rocks, whether porphyritic or nonporphyritic, may be further classified on the basis of the minerals they contain. While there are a great many kinds, only a very few of the more important ones can be described here. All the different varieties shade gradually into one another.

Granite (Fig. 7) is perhaps the most common of the distinctly grained rocks. It always contains feldspar (as the predominant mineral) and quartz, and frequently has subordinate amounts of other minerals, especially mica. Descriptive names are often employed, which indicate the leading secondary minerals; thus one may speak of a mica-hornblende granite. Granites have different colors, depending largely on that of the feldspar, and on the abundance of dark minerals. Gray and red varieties are especially common. Granite is an acidic rock. Large crystals of feldspar (less often quartz) may be scattered through a granitic ground mass of smaller (but distinguishable) grains, giving a *granite-porphyry*.

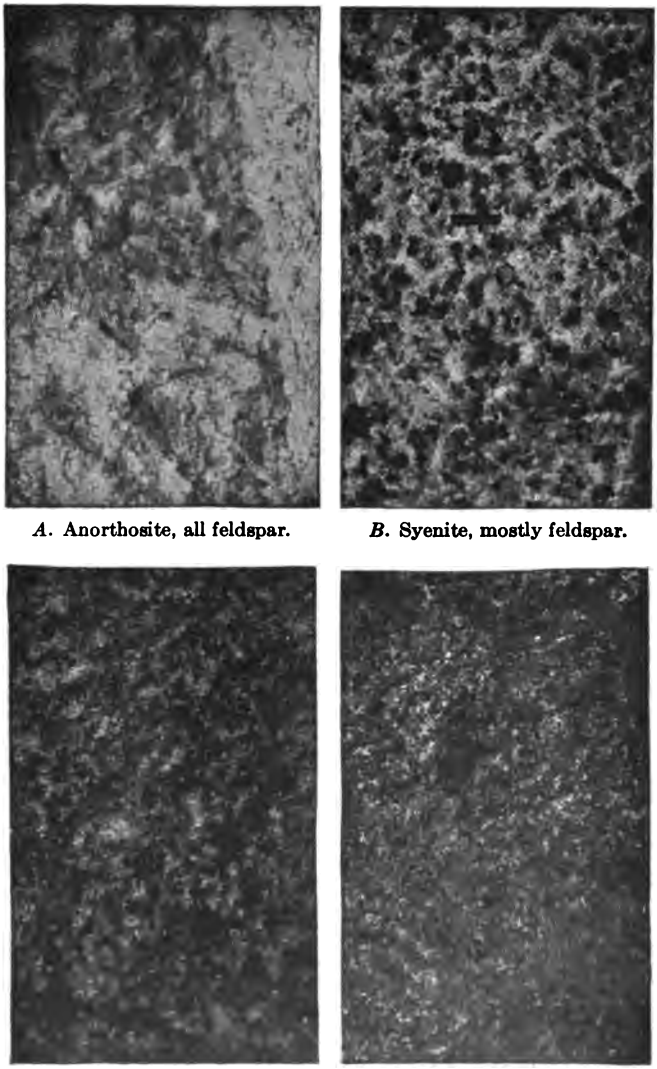
[1] For this reason there is no general agreement concerning the classification of igneous rocks. The classification used here differs from that employed in many other books.

Syenite (*B*, Fig. 10) is a rock composed chiefly of feldspar, with smaller amounts of the ferromagnesian minerals, particularly hornblende, and little or no quartz. It is usually gray or reddish, and often closely resembles granite both in color and texture. Syenite is a neutral rock. Like granite, it may have a porphyritic texture. Granite and syenite are called *feldspathic rocks* (Fig. 10), because feldspar predominates in both. Syenite is a much less common rock than granite.

Diorite is made up chiefly of hornblende and subordinately of feldspar (*C*, Fig. 10). *Gabbro* consists mainly of augite, with a subordinate amount of feldspar. Diorite and gabbro are generally dark-colored. They are sometimes not distinguishable, because it is not apparent to the naked eye whether the dominant mineral is hornblende or augite. The rock may then be called *dolerite* (meaning deceptive). Some diorites are neutral rocks, while others are basic. Gabbro is basic. Diorite and gabbro are widely distributed and common rocks.

Peridotite (*D*, Fig. 10) is a basic rock composed entirely of the dark-colored minerals — olivine, hornblende, or augite. These may occur alone or in mixtures. Both feldspar and quartz are absent. The rock is black or dark green, and is much less common than the preceding ones.

Dense rocks. — Most or all of the grains in the rocks of this class are too minute to be distinguished by the naked eye. When nonporphyritic, many of these rocks have a rather uniform, stony appearance. Such a rock, when dark-colored, may be called *basalt;* when light-colored, *felsite*. (The student must guard against confusing felsite with certain fine-grained sandstones.) Similar names are used when the texture is porphyritic; if the ground mass is light-colored, the rock is *felsite-porphyry*, if dark-colored, *basalt-porphyry*. Further subdivisions of the porphyries may be made in terms of the minerals which form the visible crystals. Thus there is quartz-felsite-porphyry, feldspar-basalt-porphyry, etc. The light rocks of this class are chiefly feldspathic, while the dark ones are mainly ferromagnesian.



A. Anorthosite, all feldspar. *B.* Syenite, mostly feldspar.

C. Diorite, some feldspar. *D.* Peridotite, no feldspar.

FIG. 10.—Contrast of feldspathic and ferromagnesian rocks. (Pirsson, *Rocks and Rock Minerals*.)

Glassy rocks. — This class includes rocks composed wholly or in large part of glass.

It has already been seen that rock formed at the surface of a lava flow is apt to be more or less filled with cavities formed by gas bubbles. Such rocks are sometimes said to have a *vesicular texture* (vesicles = cavities). *Pumice* (Fig. 11) is a rock in

Fig. 11. — Pumice, about ⅞ natural size. (Photograph by Baker.)

which such cavities take up much of the space, and are divided by very thin partitions of glassy material. Bits of pumice are found distributed widely over the ocean floor, for they are often floated long distances before their small pores become filled with water, thus causing them to sink. As the walls of the cavities become thicker and the material stony, pumice grades into *scoria* (Fig. 12). The cavities of scoriaceous lavas are sometimes partly or wholly filled at a later time by deposition of minerals from solution in ground water (Fig. 13). This, for example, is one mode of occurrence of copper in some of the mines of northern Michigan.

Obsidian or *volcanic glass* (Fig. 9) is a solid, glassy rock,

generally black in color. Its glassy condition signifies rapid cooling, while its compact texture means that gas bubbles

FIG. 12.—Scoriaceous texture. About ⅔ natural size. (Photograph by Baker.)

were not forming as it solidified. Obsidian usually has a composition much like that of granite. *Pitchstone* is a glassy rock

FIG. 13.—Amygdules in lava. About natural size. The material of the amygdules was deposited from solution in ground water in the cavities of a scoriaceous lava. (Photograph by Baker.)

which has a resinous surface, and is thought to resemble pitch in appearance. It is variable in color, — red, brown, and green varieties being common. Either obsidian or pitchstone may contain scattered crystals which can be recognized, giving rise to *obsidian-porphyry* and *pitchstone-porphyry.*

Fragmental volcanic rocks. — Volcanoes of the explosive type throw out material which falls in solid fragments. These are classified on the basis of size, shape, and texture. *Volcanic ash* is composed of very small, glassy fragments. It sometimes forms thick deposits about volcanoes. Still finer material constitutes *volcanic dust.* This is scattered widely by the winds, some slight amount probably having been carried from certain volcanoes to all parts of the world. Dust and fine ashes from Iceland volcanoes settled in 1783 on certain farm lands in northern Scotland in such quantity as to destroy crops. Such material from Krakatoa was carried several times around the earth in 1883. If the material is about the size of hickory nuts or medium coarse gravel, it is called *lapilli.* *Cinders* are made up of angular pieces of open texture, and, together with lapilli and similar fragments, form many steep-sided volcanic cones (Fig. 20). Masses of lava which have become more or less rounded because of rapid rotation in the air are *bombs* (Fig. 14). They vary from the size of one's fist or less, to a diameter of several feet. *Volcanic breccia* is a general term applied to the beds of coarser material (bombs, lapilli, coarse ashes, etc.), which accumulate around the vent. The dust and lighter ashes settle farther away to form beds of *tuff.*

FIG. 14. — Volcanic bombs, Cinder Buttes, Idaho. (Russell, *U.S. Geol. Surv.*)

Summary. — The more important points concerning igneous rocks may be summarized as follows: (1) Igneous rocks are formed by the solidification of lavas. (2) Although they contain many minerals, a few minerals make up the great mass of the igneous rocks. The most important are (*a*) quartz, (*b*) feldspar, (*c*) the ferromagnesian minerals, and (*d*) the iron oxides. (3) Chemically, igneous rocks may be divided into three great classes — acidic, neutral, and basic. (4) The physical character of igneous rocks is determined by (*a*) the character of the parent lava, and (*b*) the conditions under which it solidified. (5) Since both the composition of lavas and the circumstances attending their solidification vary widely, many kinds of igneous rocks result. Of these the few that have been mentioned are most important. They are classified in the accompanying table.

CLASSIFICATION OF IGNEOUS ROCKS[1]

A. Grained, Constituent Grains Recognizable. Mostly Intrusive				
	a. Feldspathic rocks, usually light in color		*b*. Ferromagnesian rocks, generally dark to black	
	With quartz	With little or no quartz	With subordinate feldspar	Without feldspar
Nonporphyritic	Granite	Syenite	Diorite Gabbro Dolerite	Peridotite
Porphyritic	Granite-Porphyry	Syenite-Porphyry	Diorite-Porphyry	
B. Dense, Constituents partly or wholly Unrecognizable. Intrusive and Extrusive				
	a. Light-colored, usually feldspathic		*b*. Dark-colored to black, usually ferromagnesian	
Nonporphyritic	Felsite		Basalt	
Porphyritic	Felsite-Porphyry		Basalt-Porphyry	
C. Rocks composed wholly or in part of Glass. Extrusive				
Nonporphyritic	Obsidian, Pitchstone, Pumice, etc.			
Porphyritic	Obsidian-Porphyry, Pitchstone-Porphyry			
D. Fragmental Igneous Material. Extrusive				
Tuff, Volcanic Breccia				

[1] After Pirsson, with slight modification.

The oldest known rocks are igneous rocks, or metamorphic rocks which have been produced from them. Since all other rocks have been formed directly or indirectly from igneous rocks, the latter have been called the mother rocks. Igneous rocks, or their altered products, are thought to underlie all other kinds of rocks, and to make up a very large proportion of the earth's mass.

SEDIMENTARY ROCKS

The formation of sediments. — It has been seen (p. 16) that the greater part of the land surface is covered with loose rock material formed from the solid rock. This rock waste varies greatly in size, ranging from fine clay, through sand and gravel, to large pieces of rock. It is a matter of common observation that the finer material is shifted frequently from place to place. Winds blow dust in quantity from roadways and the bare surfaces of fields. Rain sometimes washes large amounts of earth down the sides of freshly plowed hills. Streams are commonly made muddy in rainy weather by the fine silt which they carry, and they drag and roll coarser material, such as sand and gravel, along their channels. Since water always flows down slope, the material it carries is also moving to lower levels. And because all the water which does not sink into the ground, evaporate, or stop in some lake runs to the sea, it follows that much of the rock waste it moves is carried into the ocean.

If water from any stream is evaporated, a mineral residue remains. This means that rivers are carrying mineral matter to the sea in solution as well as in solid pieces. The Thames River of England carries over a ton of dissolved matter to the sea each minute on the average. It has, indeed, been declared that the one great mission of running water is to get the land into the sea. The dissolved material is likely to remain in solution in the sea water for a longer or shorter period, some of it indefinitely. Nearly all of the sediment which is carried to the sea in the solid form soon settles to the bottom,

the larger and heavier pieces first, the smaller and lighter later.

Offshore waters are frequently agitated down to the bottom by winds and tides, the undertow (a from-shore movement of the water which has come in with the waves), and by various currents. The sediment on the bottom is rolled and dragged about by these movements of the water, and is often shifted long distances before reaching a final resting place. Normally the bottom water moves most, close to shore where it is shallow, and frequently only coarse material, such as gravel, comes to rest there, all sand and mud being swept away. Farther out the quieter bottom water is able to move only mud particles, and drops any sand it may have had. Still farther from shore the bottom waters become so quiet with increasing depth that even the finest mud comes to rest upon the floor. Thus

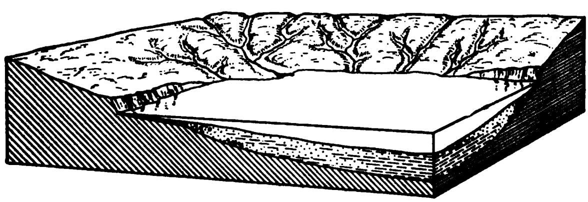


FIG. 15.—Diagram showing the relations to one another and to the land, of beds of gravel, sand, and mud.

the stream-borne waste from the land tends to accumulate in belts of gravel, sand, and mud, which merge gradually into one another (Fig. 15). Since the depth of the water and the strength of the waves and currents vary at points equally distant from the shore, different material is likely to be accumulating at these different places; traced alongshore, gravel may give way to sand and sand to mud. Furthermore, the agitation and depth of the water vary from time to time at a given place, because of alternating storms and calms, high and low tides, etc. Hence the character of sediments is subject to changes vertically as well as horizontally, and alternate layers

of gravel, sand, and mud are formed in the same place. This division into layers, or *stratification*, as it is called, is the most universal and important characteristic of water-laid beds, though not confined to them.

Countless numbers of minute organisms live in the clear and relatively quiet waters beyond the reach of abundant land-derived sediment. Many of these organisms take calcium carbonate or silica from solution in sea water, and build it into their shells and other hard parts. When they die, these shells, etc., sink, and over millions of square miles of the ocean floor form a deposit, called *ooze* (Fig. 277, p. 259). Near the shores, these organic deposits are usually less important than the gravels, sands, and muds brought down from the land.

The consolidation of sediments. — Material in solution in sea water is sometimes deposited among the particles of the sediment, binding them together to form firm, solid rocks. Furthermore, the bottom sediment is under the weight of the overlying material deposited later, and this may become effective in pressing the particles closer together, though it probably does not aid greatly in making the mass coherent.

Sea-laid sediments may be exposed by an elevation of the ocean bottom, or by a lowering of the sea surface, and ground waters containing minerals in solution may subsequently deposit material in their pores, further cementing the rocks. Rock cementation is often a very slow process, and coastal plains that have emerged from the sea recently (as geology measures time) are apt to be underlain by beds of loose material rather than of solid rock. This is generally true in the Atlantic Coastal Plain of the United States (Figs. 43 and 44, pp. 62, 63).

Certain sediments (particularly lime carbonate oozes) are consolidated not only by cementation, but also, and in some cases chiefly, by the formation of minute interlocking crystals.

Chief kinds of sedimentary rocks. — Sedimentary rocks are formed from loose sediments by (1) cementation, (2) crystallization (in some cases), and (3) pressure (to slight extent),

as indicated above. Cemented gravel is *conglomerate* (Fig. 16), while if the pieces are angular instead of roundish, the

FIG. 16.—Conglomerate. About ⅔ natural size. (Photograph by Baker.)

rock is known as *breccia* (Fig. 17). Cemented sand is *sandstone*. The common sandstone cements are lime carbonate, the iron oxides, and silica. The nature of the cement influences the color and strength of the sandstone. *Quartzite* is a dense and very hard rock, produced when the pores of a sandstone are completely filled with quartz. The sand grains of the sandstone are worn fragments of quartz crystals, and the quartz molecules deposited about them arrange themselves in accordance with the internal structure of quartz crystals (p. 21), and seek to develop again the

FIG. 17.—Quartzitic Breccia. (Neal.)

six-sided prisms. Cemented and compacted clay forms *shale*. Conglomerate, breccia, sandstone, and shale, since they are made up of fragments of older rocks, are often called *fragmental rocks*. The remains of organisms that take calcium carbonate from solution in the waters to form their shells become *limestone* when cemented or crystallized. Some limestones have been formed by chemical precipitation of calcium carbonate. *Chalk* is a very soft limestone of fine texture. *Dolomite* (magnesian limestone) is developed when some considerable proportion of the calcium of a limestone is replaced by magnesium. This replacement may take place long after the formation of the limestone, or while the material of the limestone is accumulating.

Flint is a very compact, dark gray, siliceous rock. *Chert* is an impure flint, usually of light color. These rocks do not in most cases form extended independent beds, but occur chiefly in limestones in the form of irregular masses and thin layers. Both contain fossils of the siliceous parts of various sea animals, particularly sponges and protozoans (p. 294). The silica was taken from sea water by such animals, and at their death formed deposits, often scattered through other sediments. Subsequently, some of it was dissolved by ground water, and redeposited in certain places where conditions favored. (See Concretions, p. 121.) While this seems quite certainly to be the origin of some flints and cherts, that of others is uncertain.

The larger part of the land surface is covered with sedimentary rocks. Most of these rocks are in layers and contain marine fossils. For these and other reasons, it is concluded that such rocks are consolidated sediments that were deposited beneath the sea in the same manner that offshore sediments are now forming. This conclusion carries with it the inference that at some time in the past the ocean waters have covered large areas which are now land. Since the beds of sediment now forming are nearly horizontal, we conclude further that all sedimentary beds originally had that position, and that

great departure from horizontality indicates later disturbance.

Nonmarine fragmental rocks. — While the ultimate goal of running water and of the waste it carries is the sea, much material is deposited in lakes, along valley bottoms, and in other situations on the land. These sediments, like marine beds, may become firm rock by cementation. Beds formed in lakes that have since been destroyed usually betray their origin by their form and attitude, and by the fossils which they contain (p. 267).

River deposits also have distinguishing characteristics, some of which are suggested by Figure 185. Long, relatively narrow strips of coarse material indicate former positions of the shifting stream channel, while the broader layers of fine material were spread upon the flood plain by the quieter waters of the overflow. Cross-bedding (p. 54) and great irregularity of stratification are among the most characteristic features of stream deposits. Occasionally, they contain river and land shells. River deposits will be considered in greater detail in Chapter V.

Other sedimentary rocks. — Certain special classes of sedimentary rocks, some of them very important, may best receive attention in later connections. These include gypsum and rock salt, precipitated from solution under special conditions (p. 268), the iron ores (p. 323), and a few rocks formed by organisms, or themselves organic, like coal (p. 379), together with deposits made by winds (p. 98) and by glaciers (pp. 204, 212).

Summary. — The more important points concerning the origin of sedimentary rocks are the following: (1) Loose surface material is being formed constantly by the decay and breaking up of solid rock. (2) Various agents which transport material on the land, particularly rivers, are shifting this rock waste to new situations, especially to the sea. (3) In the process of transportation and deposition it is more or less perfectly sorted, and beds of gravel, sand, and mud result.

(4) These sediments are cemented to form conglomerate, sandstone, and shale, the principal classes of fragmental rocks. (5) Limestones are formed from organic remains, and sometimes by precipitation from solution. (6) These sedimentary rocks may themselves be exposed and may decay, and the resulting waste may be carried to the sea, or other lodgment areas, to form new sediments and rocks, which may in turn experience a similar fate. In this manner many generations of sedimentary rocks have been formed, and later more or less wholly destroyed. Since all sedimentary rocks are formed from still older rocks, they are sometimes called *secondary rocks*.

METAMORPHIC ROCKS

Metamorphic means changed, and metamorphic rocks are those which, originally igneous or sedimentary, have been altered in composition, or in texture, or in both, since they were made. Metamorphism may result in the weakening and decay of rocks, or it may strengthen and consolidate them.

When rocks formed at or near the surface are buried deeply beneath later beds, they encounter conditions very different from those under which they were made. They are under the great pressure of the rocks above, and may also be subjected to lateral compression. They are affected by higher temperatures, and are acted upon by ground waters that are made powerful chemically by heat and pressure. In consequence of these things, their composition may be altered, — their minerals changing into other minerals whose chemical composition is more stable under the new conditions. They may become more thoroughly consolidated, harder, and more crystalline. They may develop also a sheeted or banded structure (Fig. 18), which is distinct from the stratification of sedimentary rocks. Similarly, when igneous rocks that were formed by the solidification of lavas at great depths are exposed at the surface through erosion, they find entirely new conditions. They are subjected to the influences of temperature changes, of the

gases of the atmosphere, of wind and water, of plants and animals, and of other agents. They commence at once to break up and decay, their constituents forming new combinations suited to the new conditions. As in the cases suggested, metamorphic changes in general are in the nature of adaptations to a new environment.

Although metamorphism, strictly speaking, includes all changes in all rocks, and may be destructive in its effects, as well as constructive, yet in common usage it implies radical changes of the latter type, in consolidated rocks. Such changes take place within the earth, especially at great depths. The processes of metamorphism are treated in later pages (78–83).

In working out its physical history, it is frequently important to determine whether the metamorphic rocks of a given region were derived from igneous or from sedimentary rocks. The answer is sometimes given by bodies of unaltered or little changed rocks within the metamorphic rocks. In some cases, more or less distorted pebbles of various kinds indicate that the parent rock was a conglomerate whose finer material has been changed greatly, while the larger pebbles were merely flattened and lengthened. Or again, it may be possible to trace the gradation from the metamorphic rocks, through less and less changed rocks, into the unaltered rocks of a neighboring area. The origin of many metamorphic rocks may be detected, too, by microscopic examination or by chemical analysis.

Gneiss (pronounced "nice") is a crystalline rock, in many cases containing the same minerals and having the same general appearance as granite, except that it is distinctly banded (Fig. 18), due to the partial arrangement of unlike minerals in separate layers. The bands may be bent and twisted in a way that suggests intense crumpling (Fig. 6). Granitic rocks usually become gneisses when metamorphosed. Gneiss may be made, however, from various other kinds of rock.

Schist is in general more closely and regularly banded than

gneiss, and exhibits a strong tendency to split into uneven leaves or plates. These plates are often spangled with glisten-

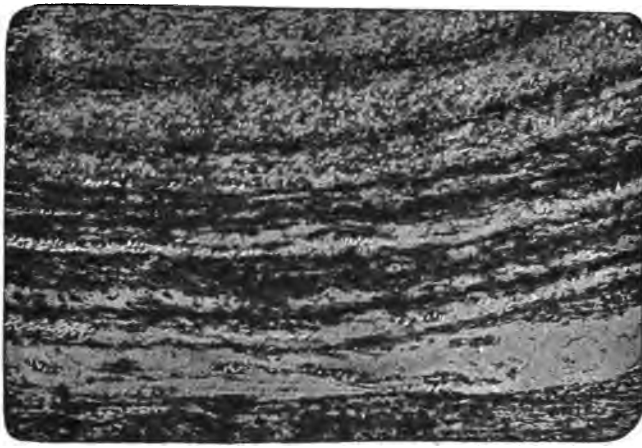


FIG. 18.—Banded gneiss. (Pirsson, *Rocks and Rock Minerals.*)

ing flakes of mica, or with needles of hornblende. Indeed, the splitting habit characteristic of schists is due largely to the presence of cleavable minerals in parallel arrangement. Many varieties of schist are recognized. *Mica schist* is most common, and consists chiefly of quartz and mica, usually with a subordinate amount of feldspar. It is often formed from slates and feldspathic sandstones. In *hornblende schist,* leaves of imperfect hornblende crystals are separated by other minerals, in many cases by feldspar, quartz, and mica. Basic igneous rocks, when metamorphosed, often become hornblende schists. The latter may be formed also from sedimentary rocks.

Slate is formed from shale by compression. It is a hard, very fine-grained rock, not obviously crystalline, usually dark-colored, and characterized by a remarkable cleavage, often so perfect that the rock is quarried extensively in parts of New England and in other regions for roofing purposes (Fig. 19). The formation of slate involves far less change than the development of gneiss or schist.

Marble is metamorphic limestone. It represents an advanced stage in the crystallization of calcareous sediments (p. 37). In some marbles the fine grains of calcite have re-formed as interlocking crystals larger than those in most granites, while in other cases the texture is so fine that individual grains cannot be distinguished. Marble is white if formed from pure limestone, but because of impurities may be of any color. Carbon and other impurities often form streaks or bands of varying color, producing beautiful and odd effects on polished surfaces. Marble is much used as an ornamental building stone. There are extensive quarries at various points in the East, particularly in Vermont. Unlike most metamorphic rocks, pure marble is without cleavage. It may be scratched easily with a knife, and thus distinguished readily from sandstone and quartzite, which it may resemble in appearance.

FIG. 19. — Fossiliferous slate near Townsend, Mont. (Walcott, *U.S. Geol. Surv.*)

A. META-SEDIMENTARY SERIES

a. SEDIMENTS	*b.* SEDIMENTARY ROCKS	*c.* METAMORPHIC ROCKS
Gravel	Conglomerate	Gneiss, and schists of various kinds
Sand	Sandstone and quartzite	Various schists (especially quartz schist) from quartzite. Mica schist from certain sandstones
Clay	Shale	Slate, and various schists (especially mica schist)
Calcareous deposits (shells, etc.)	Limestone	Marble

B. META-IGNEOUS SERIES

a. Igneous Rocks	b. Metamorphic Rocks
Granite, syenite, and other grained feldspathic rocks	Gneiss
Felsite and acidic tuffs	Various schists
Diorite, gabbro, basalt, and other ferromagnesian rocks	Various schists (especially hornblende schist)

Only the leading varieties of metamorphic rocks have been described. There are many other kinds which cannot be considered here. The general relations of those discussed to the rocks from which they are commonly derived are shown in the preceding table.

The relation of rocks to one another. — At the very outset the student is likely to encounter rocks that cannot be identified readily with any of the kinds enumerated in the preceding pages. Thus, a rock may be found which contains both sand and calcite in perhaps nearly equal proportions, and which therefore combines the features of a sandstone and a limestone. Varieties of rocks are, in fact, not definite species, as are most kinds of animals and plants. Rather, they grade into each other by imperceptible stages. By a gradual decrease in quartz, granite verges toward syenite. By an increase in hornblende and a decrease in feldspar, syenite passes into diorite. By a decrease in the size of its pebbles, conglomerate approaches sandstone. Similar transitions occur between all related varieties of rocks.

Furthermore, rocks change after they have been made, and this produces further gradations from one kind to another. Thus, as noted above, granite may be slowly altered into gneiss, and shale into slate, and slate, in turn, to schist. Shale and schist are distinct in appearance and constitution, yet all possible gradations may be found between them. It is evident, then, that rock names must be used loosely, and that there are few sharp dividing lines anywhere in the classification.

Original Structures of Rocks

By *rock structure* is meant the mode of occurrence of rocks, the shapes of rock bodies, and the position or attitude of those bodies. Thus, to say that certain rocks are stratified and that the beds are horizontal, or tilted, or folded, is to state phases of their structure. The principal original structures of rocks are discussed below, while some structures developed by the changes which take place in the outer part of the earth are described in the next Chapter.

SURFACE STRUCTURES OF IGNEOUS ROCKS

Volcanic cones. — The greater part of the material extruded by volcanoes accumulates near the vents, forming conical elevations. These *cones* vary in size and shape. They range in height from a comparatively few feet up to high mountains like Mauna Loa in Hawaii, whose summit is some 14,000 feet above the neighboring sea and about 30,000 feet above the sea floor. The slope of a cone is determined by its composition. Coarse, angular cinders stand in steep piles (Figs. 20 and 21), while the more liquid lavas spread freely and build cones whose sides in exceptional cases form angles of only two or three degrees with a horizontal plane (Fig. 22). Stiffer lavas form cones of intermediate steepness. Lava cones consist of many solidified streams of lava which flowed from the vent in different directions at different times, producing a sort of radial structure. Most cones, like Vesuvius, are built of both lava and fragmental material, and for various reasons they are often irregular in form and structure.

Fig. 20. — Cinder cone in Owens Valley, Cal. (Fairbanks.)

A majority of the existing volcanic mountains are near the

edges of the continents and in the sea, though some are far inland. With some notable exceptions, the active and recently

FIG. 21.—Lava flow (in right foreground) and cinder cones near Flagstaff, Ariz. (R. T. Chamberlin.)

extinct volcanoes are arranged in lines or belts where the earth's crust has recently undergone severe movement.

Lava plateaus. — When lavas issue from long cracks (*fissures*) in the surface, or from numerous more restricted vents, they may spread widely over the surrounding country before solidifying. The distance to which the lava flows depends upon how fluid it is, upon the amount, and upon the character

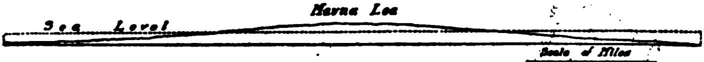


FIG. 22.—Profile of the cone of Mauna Loa, Hawaii. Vertical scale same as horizontal. (*U.S. Geol. Surv.*)

of the surface over which it moves. (What combination of these conditions would enable the lava to flow farthest?) The lava congeals first at the top, forming a crust whose surface is comparatively smooth (Fig. 23), unless it is repeatedly broken by the continued movement of the still liquid mass beneath. In the latter case the surface is extremely jagged

and irregular (Fig. 24). Successive fissure eruptions may build up great plateaus. Such a lava plateau, with an area

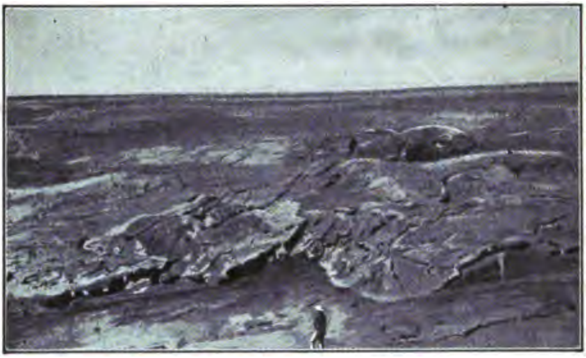


FIG. 23. — Surface of a comparatively smooth lava flow. Jordan Craters, Oregon. (Russell, *U.S. Geol. Surv.*)
How may the fissures be explained?

of some 200,000 square miles, occurs in Washington, Oregon, and Idaho (Fig. 25). The lava is locally 4000 feet in thick-

FIG. 24. — Margin of a lava flow, Cinder Buttes, Idaho. The broken condition of the lava is due to movement after the outside had hardened. Note the steep edge of the flow. (Russell, *U.S. Geol. Surv.*)

ness along the Snake River, which flows through the plateau in a deep cañon. The cañon walls show that the elevations

buried by the lava floods were in some cases mountains of considerable elevation. Lava flows built an even larger plateau in the peninsula of India.

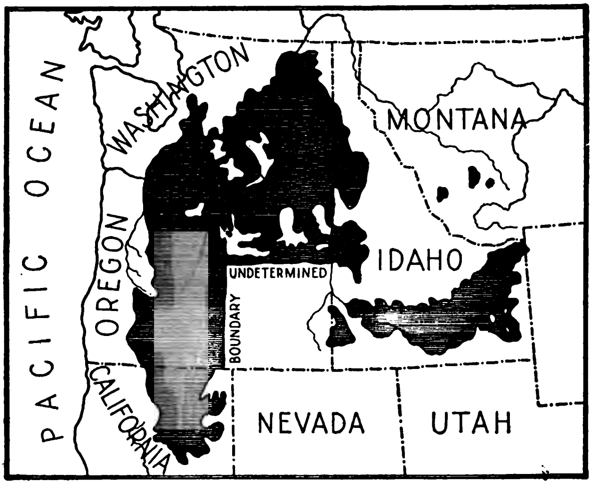


FIG. 25. — Lava flows of the Northwest.

UNDERGROUND STRUCTURES OF IGNEOUS ROCKS

Most of the lava forced upwards from great depths fails to reach the surface and solidifies underground. Igneous rocks formed from lavas deep below the surface are called *plutonic rocks*. Such rocks may be exposed at the surface through the wearing away of the rocks which overlay them. Indeed, much of the igneous rock at the surface is intrusive rock. Intrusions of lava vary in shape and in their relations to the inclosing rock. These differences have given rise to special names. Lava hardens in cracks and fissures in the rock to form *dikes* (Fig. 26). Dikes vary in thickness from

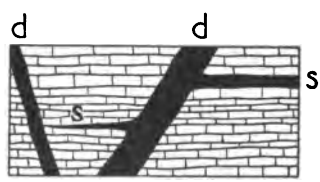


FIG. 26. — Diagram of dikes and sills. *d*, dike; *s*, sill.

a few inches to two or three hundred feet, and in exceptional cases have a length of scores of miles. In many cases dike rock is more resistant than the adjacent country rock, and hence many dikes form low, narrow ridges (Fig. 27). If softer than the rock it penetrates, the line of outcrop of the dike rock becomes a depression.

FIG. 27. — Porphyry dike cutting tuff. Southwestern Colorado. (Howe, *U.S. Geol. Surv.*)

Lava intruded between rock layers in wedge-shaped sheets forms *sills* (Fig. 26). Sheets of lava extruded upon the surface may later be covered by other rocks. Such sheets then have the position of sills, though of different origin. In working out the geological history of a region, it is sometimes important to determine whether a given lava sheet which lies between sedimentary beds is *intrusive* or *extrusive*. If the bottom of the bed resting on the lava sheet has been baked by the hot lava, which origin may be inferred? If the top of the lava sheet is glassy and has a vesicular texture? If tongues of igneous rock extend from the lava sheet into the overlying rock? By these and other observations, the problem may usually be solved.

Sills merge into dome-shaped intrusions. If these merely arched the overlying beds, they are called *laccoliths* (Figs. 28 and 29). The Henry Mountains of Utah are notable ex-

amples. If the sedimentary beds were broken and the broken edges displaced (*faulted*), the intrusion is a *bysmalith.* The Spanish Peaks of southeastern Colorado are an illustration. Deep-seated intrusions of very great size (often many miles across) are known as *batholiths.* Usually batholiths are of irregular form. Unlike laccoliths, they do not simply bulge the cover, but occupy vast spaces which have been actually hollowed out of the preëxisting rocks. Whether this was accomplished by melting and as-

FIG. 28. — Diagram of a laccolith with associated dikes and sills.

FIG. 29. — Two Buttes, Prowers County, Colo. Sandstone beds uplifted by a laccolithic intrusion. The slopes have been modified by erosion. (Darton, *U.S. Geol. Surv.*)

similating the previous rocks, or otherwise, is not known definitely. Such intrusions are of rather common occurrence in eastern Canada, in association with very ancient rocks. Erosion has removed their original covering, exposing the igneous cores. Granite batholiths form the central cores of many of the great mountain ranges. Certain bodies of intrusive rock, exposed by erosion and rudely circular or elliptical in ground plan, are called *stocks* (Fig. 30). They vary in diameter at the

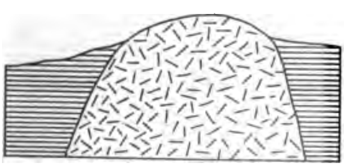


FIG. 30. — Diagram of a stock.

surface from a few hundred yards to a number of miles, and in many cases increase in size downwards, their sides cutting irregularly across the surrounding rocks. In New England, eastern Canada, and other regions, many granite stocks form hills because of the more rapid erosion of the less-resistant inclosing rocks. Stocks differ from batholiths chiefly in being very much smaller, and from laccoliths and bysmaliths particularly in their relations to the surrounding rocks. Igneous rock occurring as laccoliths, bysmaliths, batholiths, and stocks is not n beds, has no cleavage, and its crystals are without systematic arrangement. Accordingly, it is said to have a *massive structure.*

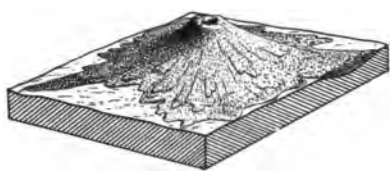


FIG. 31.—Diagram of a young volcanic mountain.

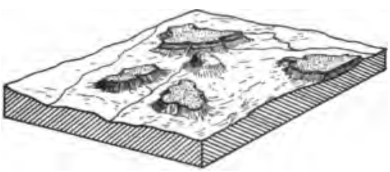


FIG. 32.—Diagram showing a volcanic neck and several mesas (p. 167) resulting from the long continued erosion of a volcanic mountain similar to that shown in Figure 31.

Volcanoes are, geologically speaking, short lived. When the volcanic forces die away or find relief through other vents, no further additions are made to the cone of a volcano (Fig. 31), which in time is worn away by the agents of erosion. Long after it has disappeared, the resistant rock formed by the slow solidification of the lava which remained in the tube leading down from the crater may remain

FIG. 33.—Volcanic neck near Adair, southeastern Colorado. A cylindrical mass of basalt occupies the throat of an extinct volcano, and is surrounded by an accumulation of talus. (*U.S. Geol. Surv.*)

as an abrupt, steep-sided hill. These elevations, known as *volcanic necks* or *plugs* (Figs. 32 and 33), range in diameter from a few yards to a mile or more. They may be regarded as monuments, marking the sites of volcanoes which died ages ago. Volcanic necks are known at various points in the West, especially New Mexico, in Scotland, and in many other places. No matter how resistant their rocks, volcanic necks are themselves finally destroyed as topographic features, leaving as perhaps the only record of the ancient volcanoes the igneous rock occupying the old tubes leading to unknown depths below. There are many examples of this stage in the West.

FIG. 34.—The Devil's Post Pile in the Sierra Nevada Mountains. Basalt which has split into columns. (*Nat. Geog. Mag.*)

Columnar structure. — The cracking of fine mud as it contracts on drying is a familiar phenomenon. In a similar way, some lava cracks on cooling, sometimes forming regular columns (Fig. 34). These are six-sided in many cases, and stand at right angles to the cooling surfaces. In horizontal sills and lava flows, therefore, the columns are vertical, while in vertical dikes they are horizontal. They occur, among other places, in the Palisades of the Hudson, and in Mount Holyoke, Massachusetts. The cracks which separate the columns are *joints*. Joints are not peculiar to igneous rocks. They affect rocks of all kinds, dividing them into blocks of various sizes and shapes.

ORIGINAL STRUCTURES OF SEDIMENTARY ROCKS

Stratification. — It has been noted (pp. 36–37) that sediments are commonly arranged in distinct layers, and that this stratification is the most important structural feature of sedimentary rocks. A layer may be called a *bed* or a *stratum* (plural *strata*). A group of consecutive layers composed of the same kind of rock is often called a *formation*. Layers are separated by more or less pronounced division planes, known as *bedding planes* (Fig. 5). An individual layer implies essentially uniform conditions of sedimentation. A notable pause in deposition, a change in the kind of sediment, or a marked change in the texture of the material is indicated by a new layer. The longer conditions remain constant, therefore, the thicker a given layer becomes. Thickness of beds is, however, only a very rough measure of time, for the same material gathers at unequal rates at different times and places. Very thin beds, such as those in shales, are termed *laminæ*. Lamination is absent or inconspicuous in pure limestones, and usually pronounced in shales.

FIG. 35. — Cross-bedded sandstone, cañon of Virgin River, southern Utah. (Fairbanks.)

Cross-bedding. — If a current (of water or air) moves material along a surface which terminates in an abrupt slope, most of the material will roll down the slope and come to rest. Coarse material will rest at a steep angle, and fine material at a gentler angle. If the coarseness of the material moved forward to the slope varies frequently, numerous inclined laminæ will be formed. If, in addition, the direction and strength of the

currents change frequently, the inclined laminæ will slope in different directions, and meet each other at various angles. This structure is called *cross-bedding* or *oblique lamination* (Fig. 35). It is especially characteristic of deposits made by streams, and is found in many wind deposits (Fig. 83, p. 94). It is developed also off ocean and lake shores, where the water is shallow enough to be agitated frequently at the bottom. Conglomerates and sandstones are cross-bedded more often than other kinds of sedimentary rock (Why?).

Ripple marks. — The rhythmical movement of shallow waters often develops on the bottom miniature ridges, commonly an inch or two from crest to crest. Such ridges are known as *ripple marks* (Fig. 36). Often they may be ob-

FIG. 36. — Ripple marks upon a sandy beach, at low tide. (Greger.) From which direction did the waves which formed the ripple marks come?

served on the sandy beds of clear and shallow streams. Here the rudely parallel ridges extend crosswise of the current, each having a relatively long and gentle slope upstream, and a shorter and steeper slope on the downstream side. Sand grains are rolled by the current up the gentle slope to the crest, whence they fall down the steep slope into the trough. By a continuation of this process, the ridges shift slowly in the direction of the current. Ripple marks are produced, too, along lake shores and seacoasts, particularly by undulatory movements of the undertow, out to depths of twenty to thirty, or even more feet. (What things determine how far from shore they may be formed?) Ripple marks may be preserved in the consolidated sediments, and are especially

common in sandstones. Ripple marks are also formed in sand by wind (Fig. 89, p. 97).

Sun cracks.—When the water in roadside pools evaporates, the bottom mud shrinks and cracks, forming the familiar *mud cracks* or *sun cracks* (Fig. 37). If the clay particles were of uniform size, and drying equal everywhere, the shrinkage cracks would probably be arranged in regular figures, after the manner of certain cooling lavas (p. 53). As these conditions seldom hold, the cracking is usually irregular. Sun cracks may form extensively in sediments that are exposed along seashores during low tide, in dry interior basins on the smooth mud floors of shallow and temporary lakes (*playas*), and about lake borders and along stream courses when the water is low. If the sun-cracked surface is exposed for a sufficient time, it will harden enough so that the cracks will not be washed out readily by the returning waters, which may fill them with other material and so preserve them permanently (Fig. 38). (In which of the above situations are the chances for preservation best? Why?) Shales contain sun cracks more often than do other rocks.

FIG. 37.—Mud cracks. (Fairbanks.)

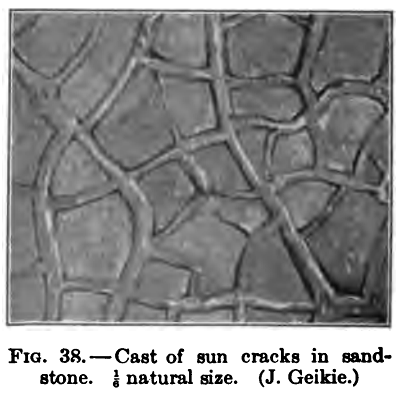


FIG. 38.—Cast of sun cracks in sandstone. $\frac{1}{6}$ natural size. (J. Geikie.)

Above features aid in determining geology of past times. — One may infer from the composition and structure of sea-laid rocks the character of the waters in which they formed and something of the nature of the lands which furnished the sediments. A conglomerate or sandstone formation of marine origin tells of shallow, rather rough waters, and of relatively high lands whose vigorous streams were able to carry coarse material. Shallow water origin may be indicated further by frequent alternation in the degree of coarseness, by cross-bedding, ripple marks, or sun cracks. If the formation contains fossils, they are likely to be the remains of animals which inhabit water of slight depth. No one formation would be apt to show all these features, but many formations show several of them. A sea-laid shale formation implies bottom waters too quiet to carry away mud. The presence of ripple marks would, however, record some agitation of the bottom water, while sun-cracked shales must have gathered close inshore where wave and current action was weak and streams did not furnish coarse sediment. If muds accumulated extensively along the ancient shore, the adjacent land must have been so low that its streams were sluggish and therefore unable to carry coarse material. The fossils of many limestones represent organisms which live only in clear, quiet waters. Such limestones may have formed close to shore if the land was sufficiently low, and protected from wash by vegetation.

In a similar way the composition and structure of non-marine formations throw light on the conditions which existed when the rocks were forming.

The principles indicated here will be applied frequently in the historical chapters, in determining the geography of North America at the several stages of its development.

Questions

1. Acidic lavas are in general stiffer than basic lavas. Which should you expect to be the leading type in (1) lava flows, (2) sills, (3) laccoliths?

2. Which of the two dikes in Figure 39 is the older? Reasons.

3. What is the age of the lava sheet *L* (Fig. 40) in comparison with the age of the sedimentary beds *S* and S_1, (1) if the lava sheet is *intrusive*, (2) if it is *extrusive?*

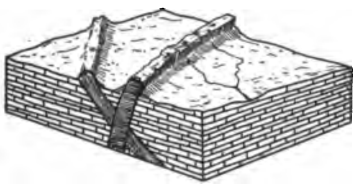


FIG. 39. — Diagram of dikes.

4. What is the relative age of the dike and the sedimentary beds (S, S_1, and S_2) in Figure 41?

5. Compare and contrast the texture of the rock in a thin and a very thick dike; at the surface and in the central portion of a massive lava flow.

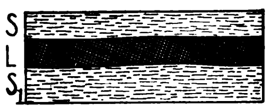


FIG. 40. — Diagram of lava sheet between sedimentary beds.

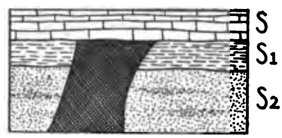


FIG. 41. — Diagram of dike and associated sedimentary beds.

6. Did the lava of the bombs shown in Figure 14 solidify before or after striking the ground? Reasons.

7. Might the fact that a given lava plateau had been built up by several distinct flows be told by the texture of the rock? If so, how?

8. How do igneous rocks come to be at the surface?

9. Coarse-grained granites, schists, and gneisses outcrop at many points in the uplands of southern New England. Where were these rocks formed with reference to the surface? What inference, therefore, may be made concerning the amount of erosion which has occurred in the region?

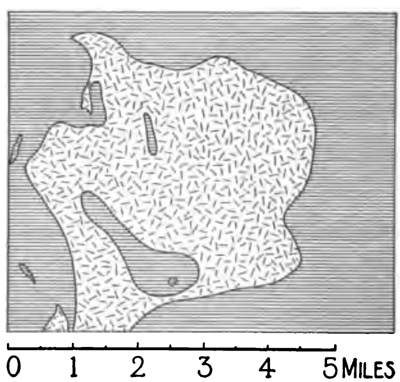


FIG. 42. — Generalized map of small area southeast of Port Orford, Ore. Short lines represent igneous rocks; horizontal lines sedimentary rocks, with some metamorphics.

10. (1) What is the rela-

tive age of the igneous and sedimentary rock (Fig. 42) (*a*) if the former is extrusive, (*b*) intrusive? (2) What hypotheses may be advanced to account for the isolated areas of sedimentary rock within the igneous rock area? How could these theories be tested in the field? (3) How could one determine in the field whether the igneous rock is intrusive or extrusive?

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CHAPTER II

PHYSICAL CHANGES OF THE OUTER SHELL

The earth's crust. — In studying the solid part of the earth, we are necessarily limited to a thin shell near the surface. In the deepest mines and cañons we may go down to a depth of a little more than a mile. By the slow denudation of the uplifted lands, rocks which were once buried to a depth of several miles may be uncovered at the surface. This outer shell, which alone is open to investigation, is the subject of the present Chapter. It has often been called the "crust of the earth," in allusion to an older theory that the interior is so hot as to be liquid, but is covered by a thin, solid crust. Although this theory has been largely abandoned, the term is convenient, and we shall use it to mean simply the outer part of the earth, which is partially open to observation.

Surface features of the crust. — The outside of the earth has an irregular surface. A glance at a model of the globe shows that there are several broad, smooth tracts, which are sunk on an average of about two and one half miles below the surface of the sea. These are the great ocean basins. Between them large plateaus stand out in relief (Fig. 43). The so-called continents are merely the portions of these plateaus that are now out of water, and hence are land. The great surface features of the earth are, then, the oceanic depressions and the continental plateaus.

Upon examining these major features in more detail, we find that the surface of the land is notably rougher than that of the sea bottoms. On the former we see mountains, ridges, and minor plateaus, with their complementary valleys, basins,

and lowlands (Figs. 43 and 44). Some of the basins contain lakes or seas, while others do not. In the oceans likewise there are irregularities, such as projecting islands, and the hollows known as "deeps"; but, on the whole, the ocean

FIG. 43. — Photograph of a relief model of North America.

floors are far less rugged than the lands. This is due partly to the fact that streams, glaciers, and other agencies which roughen the land surface do not operate in the oceans, and partly to the fact that the deposition of sediment upon the sea bottom tends constantly to smooth out such irregularities as may exist.

Movements within the crust. — As a matter of human experience the earth seems to be firm and stable to the last

degree, save for such exceptional and sudden disturbances as landslides and earthquakes. But an examination of the rocks of almost any region discloses evidence of movements which have taken place, and there is even proof that such

FIG. 44. — Chief topographic divisions of North America. Compare this with the photograph of the model on the opposite page.

movements are continually recurring. Indeed, the study of geology can hardly fail to emphasize the fact that the earth is forever undergoing changes of many kinds, which after long lapses of time produce great results. These changes include crustal movements of one kind or another. Some of the

movements are sudden, like those which produce earthquakes, while others are very slow.

The most effective movements are the slow ones, — so slow that in comparison the hour hand of a watch is revolving rapidly. We cannot readily detect such changes while they are in progress, but their results, after long periods of time, are obvious. Slow movements of this sort affect everything from whole continents to the smallest invisible particles of rock. Some of them may now be considered in more detail.

Warping of the surface. — On the slopes of Mt. St. Elias, in Alaska, modern sea shells have been found attached to the

FIG. 45. — Folded beds of limestone on the south coast of Alaska. (Stanton and Martin, *U.S. Geol. Surv.*)

rocks just as they once grew, but several thousand feet above the sea level. It appears that the coast has been slowly raised above the sea to that extent. Conversely, on the shores of North Carolina, stumps of trees are found standing out in salt water, where they did not grow. From this it becomes evident that either the land has gradually sunk beneath the sea, or the sea has risen upon it. There are many other facts which prove that the surface of the earth is rising in some places and sinking in others, but so slowly that we do not perceive it. Slow upward and downward

movements of this sort may be included under the term *warping*.

Local crumpling of the shell. — Before they were consolidated, the stratified rocks were merely layers of sediment which had been deposited in a horizontal or gently inclined attitude. In many places, however, we now find them crumpled and folded (Fig. 45). The folds in any one area are usually parallel to each other, and are arranged in long, narrow bands. Such folds have evidently been produced by compression from the sides, the part between having wrinkled, just as flat-lying sheets of paper will wrinkle if compressed horizontally.

Both the vertical movements mentioned above and these lateral movements change the surface features of the earth. The former produce plateaus, plains, and broad depressions, while the latter make mountain ridges with troughs between.[1]

Causes of crustal movements. — What are the causes of these movements? This question cannot now be answered satisfactorily. The fact that these movements take place is undeniable, but the causes of them are not yet fully understood.[2]

EFFECTS OF MOVEMENTS

Having now in mind the general nature of these slow movements within the crust, we are in a position to study the effects which they produce in the rocks. These effects may be grouped as *folds* on the one hand and *fractures* on the other.

Fracturing and folding of rocks compared.—Rocks in general are brittle substances. If quickly bent or squeezed, they will break. If, however, the pressure is applied very slowly, and especially if the layer is kept heavily weighted

[1] Mountains, plateaus, plains, troughs, and basins are formed, not only by body movements, but in a variety of other ways, which are discussed in later Chapters.

[2] The theories relating to crustal movements are discussed at some length in larger textbooks, such as Chamberlin and Salisbury's *Geology*, Vol. I, 2d ed., Chap. IX.

down by thousands of feet of rock lying upon it, a bend may result instead of a break. Since both of these conditions exist in the crust, we actually find the rocks broken in some places and bent or folded in others. In fact, different kinds of rock may show both types of structure in the same place, — the stronger rocks being broken, while the weaker are folded.

Folds

Kinds of folds. — On examining the layers (or *strata*) of rock over a large area we may find them flat in one place, wavy or rolling in another, and intricately twisted and crumpled in a third, with all gradations between. Thus we may describe folding in general as simple or complex; as mild or intense.

The individual folds may be classified from a variety of points of view. Simplest of all would be a grouping according to their attitude. Thus, all folds are either down folds (*synclines*), up folds (*anticlines*), or stepfolds (*monoclines*). Usually anticlines and synclines are combined in a series of undulations, the former making the crests and the latter the troughs of the waves.

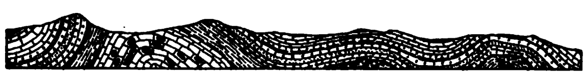

FIG. 46. — Gently folded sedimentary rocks in the central part of the Appalachian Mountains. (*U.S. Geol. Surv.*)

Before going further into the consideration of folds we may stop to examine the parts of a single simple fold: Each consists of two limbs, rising to a crest in the anticline and descending to a trough in the syncline. The inclination of the limb of a fold is called the *dip*. In field studies the angle and the direction of the dip are of much importance. The dip is always measured downward and from a horizontal plane. Thus a limb having a dip of 5° would be nearly level, while one with a dip of 90° would be vertical.

When many anticlines or synclines are compared, it is found that they present a wide variety of forms. Thus there are low, broad folds (Fig. 46), sharp folds (Fig. 47), tightly

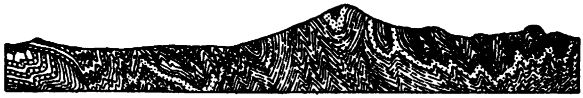

FIG. 47. — Closely folded strata in the southern part of the Appalachian Mountains. (*U.S. Geol. Surv.*)

compressed folds, and even inclined or overturned folds (Fig. 48). A layer of rocks may be bent into any of these forms according to the conditions under which the pressure was applied.

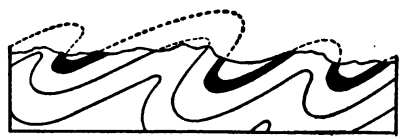

FIG. 48. — Overturned folds.

Competent and incompetent folds. — It is often advantageous to classify folds according to their *competency*. In order to form an anticline a layer must have a certain amount of strength. This will be readily apprehended if we imagine several layers of loose sand to be compressed on each side, — they would be mashed without definite folding. As compared with loose sand or mud, we can well understand that firm beds of sandstone or limestone would be likely to buckle up in the form of folds. Beds which are strong enough to hold themselves up in arches have been called *competent strata*, while materials which may be squeezed and crushed together are *incompetent*.

In considering competency, however, it is necessary to take into account something more than the character of the rock. Sheets of paper lying free upon the table, when compressed sidewise, will arch into a fold and, under those conditions, are competent. Nevertheless if several books are piled upon the sheets, the latter will not arch when compressed, but will merely be crumpled into many little twisted folds. Similarly any layer of rock, however strong, may be so weighted down by overlying beds that it will be complexly

crumpled instead of being folded in a series of simple waves. We therefore see that a given stratum may be competent if not much weighted, but incompetent if heavily loaded by reason of its burial deep beneath the surface.

In accordance with these facts there are two types of folds, one characteristic of the surface layers and the other of the great depths. When a given region is subjected to compressive horizontal forces, the layers at the top may arch and buckle into open folds; while those thousands of feet beneath may be mashed and crumpled into many little broken parallel crenulations (Fig. 49). Between these there is, of course, a transition zone wherein the weak rocks such as shale will be crushed, while the stronger limestones and sandstones may be merely bent.

FIG. 49.—Incompetent folds in jasper containing streaks of iron ore. (*U.S. Geol. Surv.*)

Compare the thickness of the beds near the crests and troughs of the folds with the thickness along the limbs. Why the difference? Would the same be true of competent folds?

Folds considered in ground plan. — Thus far we have been viewing folds in cross section. In order to see them as they really are we must add the third dimension and regard them also in ground plan.

One of the simplest types of fold is the dome, in which the strata dip away equally in all directions from a central point. But the majority of folds are more or less elongated in one direction. If unaltered by erosion, they would form long ridges and troughs, gradually decreasing in relief toward either end. But since almost all the folds we have in nature have been eroded, — many of them having been completely planed down, — it is better to consider them in their truncated con-

dition. In such a fold we find a definite axis. At the sides, the edges of various strata are nearly parallel to this axis. These edges are *outcrops,* and their shapes depend on the

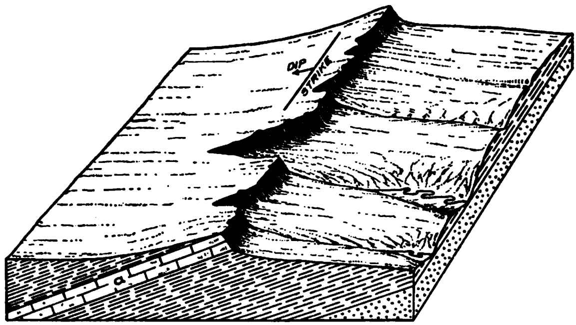

FIG. 50. — Diagram illustrating the difference between strike and outcrop. How has the cutting of the valleys affected (1) the outcrop, and (2) the strike? What would be the effect if the beds (1) dipped to the right, (2) were vertical?

attitude of the underlying beds and upon the configuration of the hills and valleys (Fig. 50). The *strike* of the beds is the

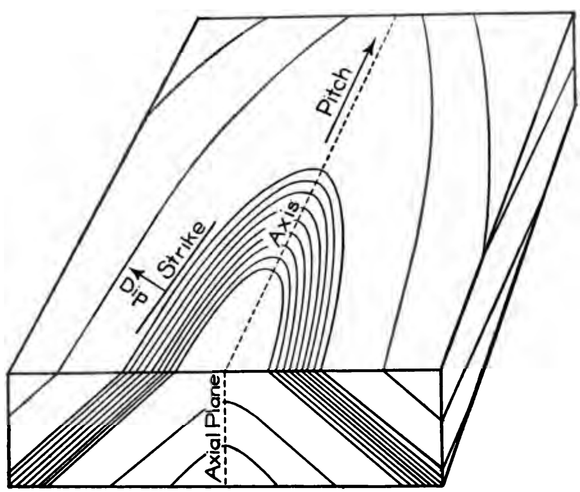

FIG. 51. — Stereogram of one end of a pitching fold, the top of which has been cut off.

line made where the inclined stratum is cut by a horizontal plane; and it will be seen that it is always at right angles to the direction of the dip of the same beds.

Obviously a fold cannot be indefinitely long. It dies out at either end, or in other words, the axis itself is gently arched and slants downwards in opposite directions from the highest point of the fold (Fig. 51). This slant of the axis is called the *pitch* of the fold and is to be carefully distinguished from the dip of the beds. In a circular dome the angle of pitch is the same as that of the *dip* of the strata, but in all other folds it is less, except along the axis. Among synclines the features are much the same except that the pitch and dip are directed inward toward the bottom of the trough and the order of succession of the strata, as they outcrop on the surface, is reversed.

Fractures

Joints. — The uneven risings and sinkings of the crust tend to crack the brittle strata in every direction. Certain rocks, such as drying mud and cooling lava, crack also because of contraction. Every quarry and outcrop shows parallel systems of cracks, usually upright where the rocks have not been folded, but in many other places slanting. These cracks are known as *joints* (Fig. 52), because of their rude resemblance in some instances to the joints between the blocks in a stone wall.

Fissility. — When the cracks are closely spaced and parallel to each other, the rock breaks readily into plates. Slates and other rocks in which such fracturing prevails are said to be *fissile* (Fig. 53). Almost any rock may be either fissile or jointed, or both, according to the conditions to which it has been subjected. These conditions will be dealt with in later pages.

Normal faults. — Cracks thus divide the rocks into a multitude of blocks of various sizes. These blocks are sometimes tilted, shifted, or let down, so that the ends of the broken strata no longer match. Such dislocations are called *faults.*

Individual faults differ widely among themselves, and to classify or interpret the many kinds is a matter of much complexity. It has been customary, however, to group the majority of them in two divisions: (1) *normal faults,* and (2) *reversed faults.*

FIG. 52. — Three systems of joints in a hard, brittle rock. (Weidman.)

Normal faults are often produced by warping; they imply a stretching of the outer part of the crust (Fig. 54). The fault planes are almost invariably steeply inclined or vertical. The moved block may have slipped either vertically, diagonally, or horizontally. It is often possible to ascertain the direction of this slipping by means of the polished grooves, called *slickensides,* which are produced by the grinding of the one mass of rock over the other. The vertical distance between the broken ends of a given stratum measures the amount of displacement and is called the *throw* of the fault (Fig. 55). The two sides are designated as the *upthrow* and

downthrow sides, and it is important to note that in normal faults the plane of slipping slants down *away from* the upthrow side.

Fig. 53. — Fissility in highly tilted beds of slate. (Gilbert, *U.S. Geol. Surv.*)

Reversed faults. — Where the rocks have been compressed instead of stretched, the strata may be broken as well as folded. Thus the second type of faults is produced. In such cases the lower and therefore older rocks are shoved up and over the higher and younger. This is the reverse of the condition in a normal fault, hence the name. Some reversed

faults or *overthrusts* are known to have been caused by the excessive overturning of a fold (Fig. 56); but in other cases

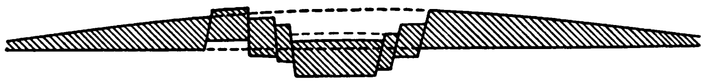

FIG. 54. — Diagram of normal faults in a segment of the earth's crust.

the rocks have merely been sliced through by a diagonal fracture (Fig. 57).

Reversed fault planes are usually not steeply inclined Some, indeed, are almost horizontal. In the mountains of North Carolina great masses of the older rocks have been thrust along gently inclined fractures for distances as great as 15 miles.

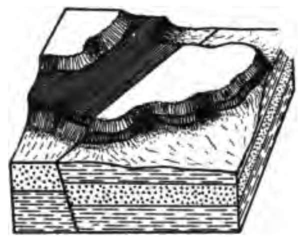

FIG. 55. — Block diagram of a normal fault.

Earthquakes. — The dislocations which result in faults, especially normal faults, are often felt at the surface as earthquake shocks. Minute slippings in the rocks give rise to mere tremors, which, although of common occurrence, are often imperceptible to our senses. Their existence is detected by

FIG. 56. — An overturned fold passing into a reversed fault. (After Heim.)

means of a delicate instrument known as the *seismograph.* Greater ruptures of the crust generate more violent shocks which often dislodge huge masses of loose rock from moun-

tain slopes, and, where they affect cities, may become highly destructive to human life and property. The Alaskan earthquake of 1899 resulted from a sudden displacement of more

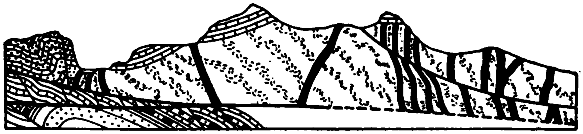

FIG. 57. — Overthrusts in the Highlands of Scotland. (*H.M. Geol. Surv.*)

than 40 feet; and the San Francisco disaster in 1906 was caused by a horizontal displacement of 5 to 20 feet (Fig. 58), which took place along a line many miles in length. Other

FIG. 58. — Displacement of a road where crossed by a horizontal fault. (Jones.) The San Francisco earthquake of 1906 was a result of the faulting.

subterranean shocks, such as those attending volcanic eruptions, may likewise produce violent earthquakes.

The destructiveness of earthquakes is due to the suddenness of the shock. Thus a sharp blow struck on the side of a table will cause very little motion in the table itself, but it may be sufficient

to overthrow completely any loose objects upon the table. When an earthquake disturbs the sea bottom a series of waves is set in motion, as in a pan of water sharply tapped on the side. These earthquake waves (often wrongly called "tidal" waves) rush upon the shore and, as in the Sicilian earthquake of 1908, may wash away houses with all their occupants, and may even dash large ships high upon the beach.

Slow growth of faults. — Almost all large faults, whether of the normal or the reversed type, have probably grown through a series of small slips separated by years or centuries in which no movement occurred. Along the great fault at the east base of the Sierra Nevada in California (Fig. 457), the vertical displacement now amounts to several miles; but the last important movement along this fracture occurred as long ago as 1872, and at that time the dislocation was increased by only 25 feet. If so great a fault were to be made all at once, the shock would probably wreck every building within hundreds of miles. Most faults grow so slowly that the *scarp* (cliff) on the upthrown side meanwhile suffers much from the work of weather and running water and comes to be furrowed by many ravines.

Unconformities

In many places the older beds of rock are folded or faulted or are cut by intrusive bodies, whereas the younger beds are undisturbed. Thus in Figure 59 the upper layers do not conform in structure to those beneath. The lower strata were doubtless nearly level when first deposited. If so, they have since been tilted in connection with folding movements; but the tops of the folds were worn off before the sediments which formed the upper strata were laid down. The two sets of layers are therefore said to be unconformable and the contact is an *unconformity*.

Not all unconformities show such a discordance of bedding. A bed of sandstone deposited on the surface of a planed-down mass of granite shows just as clearly that the surface was

deeply eroded before the sand was spread over it (Why?). Likewise an irregular weathered surface between two parallel beds indicates that deposition was interrupted after the first layer was deposited and that erosive processes carved the

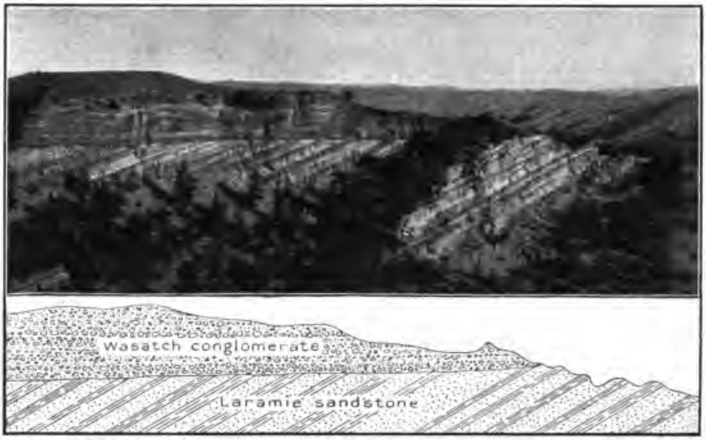

FIG. 59.—An unconformity in Wyoming. (Fisher, *U.S. Geol. Surv.*)

irregular surface before deposition was resumed in forming the upper layers. Although not so conspicuous, these also are cases of unconformity.

It is obvious that unconformities give important evidence of changes that have taken place in previous ages. Their significance is further discussed in later chapters.

VULCANISM

Rise of lava through the crust.—The rise of molten rock from unknown depths into the outer crust may be observed and is proved also by many other facts. How it becomes molten, how far down it originates, why it rises to the surface, and how it makes its way, are difficult problems, none of which has thus far been satisfactorily solved.[1]

[1] The many theories which have been suggested to answer these questions are discussed in some of the larger textbooks of Geology.

As noted in the preceding Chapter, lavas which have succeeded in reaching the known outer part of the lithosphere produce various structures and effects. They may solidify beneath the surface in bodies of vast size; they may bulge the overlying rocks in blister-like form; they may fill cracks and bedding planes; and they may even reach the surface, there to be poured out as lava flows or be blown into dust and cinders. Doubtless that part which solidifies in the form of batholiths, stocks, and laccoliths far exceeds the portion which has been built into surface plateaus and the familiar volcanic cones. All of these are effects of one great process, *vulcanism.*

The building of characteristic structures and the formation of igneous rocks is not the only conspicuous effect of vulcanism. The lavas may bake the rocks which they penetrate. The hot gases and solutions, which most bodies of lava emit as they cool and crystallize, spread out through cracks and pores in the surrounding rocks and deposit quantities of minerals which they originally held in solution. By these means the *country rock* may be considerably altered.

ZONES OF FRACTURE AND FLOWAGE

As compared with other things familiar to us, rock is one of the hardest and strongest materials. Nevertheless, as we have already intimated in describing folds, there is a limit to its strength.

At the surface the rock lies under the weight of the atmosphere only (about 15 pounds per square inch). At a depth of one mile there is added to this the weight of a column of rock one mile high, or about 6300 pounds per square inch. This is enough to crush the softer limestones and sandstones. At a depth of 6 miles or more the pressure is so much greater that even the strongest rocks cannot resist it. Each grain is compressed into the smallest space it will occupy, and any cavities or pores existing in rocks at that

depth must be tightly closed. Into this deep zone, then, water cannot readily penetrate, because there are no cracks and pores to afford it passage. If crustal movements take place, these deeply buried rocks cannot break, but the overwhelming pressure forces them to yield or flow like a plastic mass of putty. This deep zone has therefore been called the *zone of flowage.*

At and near the surface almost any rock is strong enough to maintain open fissures, cavities, and pores. Crustal movements there tend to crack the rocks, the pressure being insufficient to mold them. The upper zone is therefore called the *zone of fracture.*

Between these two zones is a transition zone in which the weaker rocks, such as shale, yield to the pressure; while strong rocks, like quartzite and granite, remain rigid and may support open fissures.

How Rocks are Altered

Like most other substances, rocks may be radically changed by subjecting them to great pressure, heat, and the solvent action of water. Some of these alterations result in the decay of the rocks, some in further hardening, and some in a reorganization of the minerals of which the rock is composed. These changes are in turn the cause of differences in the color, strength, structure, and texture of the rock. A red sandstone may be changed into a hard, black quartzite; a massive basalt may become a slaty green schist; and a dense limestone may be altered to a coarse-grained marble.

Alterations in the zone of fracture. — The rain water which sinks into the soil accumulates in the pores and cracks in the rocks beneath. Except near the surface it completely saturates the rocks, and the body of water thus formed is the source of our wells and springs. At first the water goes chiefly downward; but soon it begins to travel devious paths through cracks and porous layers, many of which lead it in

horizontal or diagonal directions. Afterward a part of it may issue at lower points in springs. To this pervasive circulation of water are due many of the most important changes which rocks undergo.

In its early downward course, percolating water dissolves out of the rocks the more soluble materials. This renders the rocks more porous and decayed, until they crumble, leaving the less soluble sand and clay to form the soil. These in turn are likely to be carried off by winds, streams, and other agencies and deposited as beds of sand and mud, which may eventually become sandstone and shale.

In the course of its descending journey the water thus becomes saturated with various mineral materials. When in this state a slight change in the temperature, or other surrounding conditions, may be sufficient to cause the deposition of some of the dissolved substance. Thus quartz may crystallize out of a solution which is slowly seeping through a porous bed of sandstone and may, by filling up the pores, produce a firmly cemented *quartzite* (Fig. 60). Only a part of the mineral matter taken into solution during the decay of the rocks is used up in this way; some of it is carried out through springs, joins rivers, and is finally poured into the sea.

FIG. 60. — Quartzite as it appears under the microscope. The individual sand grains may still be identified by their rounded outlines, but the interspaces are completely filled with quartz.

Minerals often crystallize upon the walls of a fissure through which a water solution is rising, and by this process the crack may be completely filled. The result is a *mineral vein.* The commonest vein minerals are quartz and calcite; but occasionally rare and valuable minerals, such as gold, silver, compounds of lead, zinc, and

copper, which happen to be dissolved by the waters elsewhere, are deposited in veins. A fissure with a valuable metalliferous filling of this sort is an *ore vein* (Fig. 61).

Thus it appears that the zone of fracture may be divided into two fairly distinct belts according to the nature of the changes which affect the rocks. Near the surface, and especially above the top of the body of underground water, the rocks are partially dissolved and tend to decay. This is the *belt of weathering*. At greater depths, and chiefly in the region where the rocks are saturated with water, pores and cracks are gradually filled and the whole mass becomes cemented. This is the explanation of the singular fact that many deep mines are dry; there are no longer any passageways through which water may flow. In this *belt of cementation*, marked chemical changes in the minerals themselves are in progress, resulting in the formation of new minerals out of old ones. Thus garnet may change to chlorite, and augite may become hornblende.[1]

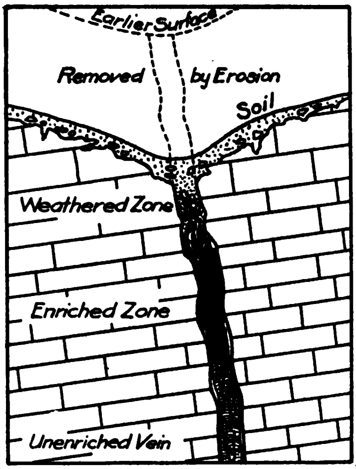

FIG. 61.—Diagram of a copper vein. The entire vein was once rather lean like the lower part, but as the surface was lowered by erosion much of the copper ore removed soaked down into the vein below and there formed a particularly rich deposit (solid black).

Alterations in the zone of flowage. — With the pressure so great as it must be beneath 5 to 6 miles of solid rock, it

[1] When a mineral is thus changed gradually into one of different composition, without altering the original form, the result is a *pseudomorph*. Petrified wood, although not originally a mineral, is a pseudomorph in this sense.

will surprise no one to learn that the mineral grains are there crushed into minute fragments and packed closely together. Firm quartzites may be mashed or granulated until all trace of the original sand grains is lost; and in coarse granites scarcely a crystal may be left in its original size or shape.

But other influences besides pressure are at work. Many things indicate that the earth is hot within. The deepest mines are uncomfortably warm even in midwinter. Volcanoes and hot springs scattered widely over the surface tell of much greater heat beneath. In mines and borings the temperature rises on the average about 1° for every 60 to 90 feet of descent. If this rate holds good, the rocks in the zone of flowage should be hotter than 350° C. (= 662° F.).

Water is another factor. Although it is true that the circulation of water in this deep zone is greatly impeded by the general lack of cracks and pores, yet water is everywhere present; and, at such high temperatures, it may be in the form of steam, notwithstanding the great pressure.[1]

This superheated water or steam is a powerful solvent. In it many minerals dissolve, and they may crystallize out again in new forms, which are better adapted to the pressure. The new minerals produced are usually heavier and denser than those which were dissolved, for in a dense mineral the same amount of material occupies less space, a change demanded by the overpowering pressure.

As the new minerals crystallize, it is easier for them to grow at right angles to the greatest pressure than directly against it. Thus all the crystals generally come to be elongated in the same direction, and the rock takes on a banded or streaky

[1] Water passes into steam at 100° C. (212° F.) under the ordinary pressure of the air at sea level. Under twice that pressure it boils at 120° C. (248° F.); and at ten times the air pressure, at 180° C. (356° F.). Above 356° C. (673° F.) steam cannot be forced into the liquid state by any pressure that has ever been applied. This is called its *critical temperature*.

FIG. 62.—Gabbro as it appears under the microscope. The white bodies are feldspar, the shaded bodies augite, and the black spots magnetite. The irregular forms of the crystals are characteristic of unmetamorphosed igneous rocks.

aspect (Figs. 62 and 63). Where the cleavage planes of the minerals are parallel to the crystals, the whole rock may split readily along them, and the result is *schist*, if the crystals are large enough to see, or *slate*, if the rock is dense.

The result of these processes is a more or less complete change in the character of the rock. Although the mashing and grinding down of the particles tend to produce a loose, fine-grained rock, the crystallizing of the material, on the other hand, produces a firm, coarser-grained rock, which also is usually banded or cleavable.

Rocks which are invaded by hot lavas from below are subjected locally to conditions not unlike those of the zone of flowage. Under the influence of the high temperature and of the hot solutions and gases which emanate from the lava, many rocks recrystallize and undergo other radical changes. A limestone may become a hard crystalline rock charged with crystals of garnet, hornblende, and other new minerals. Shale may be

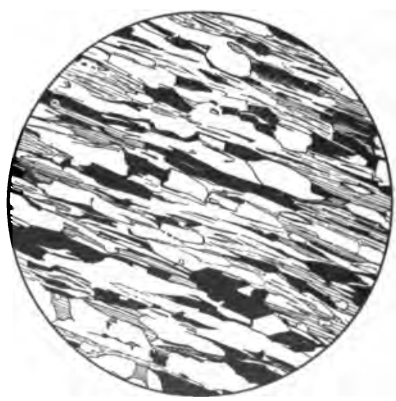

FIG. 63.—Schist as it appears under the microscope. The black, white, and shaded bodies are mineral particles of three different kinds.

What would be the direction of cleavage in this rock?

baked into a dense flinty rock in which the microscope shows that an abundance of little crystals have formed. Since pressure may be much less effective here than in the deep zone, the rocks altered along volcanic contacts do not generally possess the cleavage and banded structure which are the results of recrystallization under great compression.

The metamorphic cycle. — When the changes of the two zones are put together, it is seen that they form part of a nearly complete cycle of alterations. By way of illustration let us take an igneous rock, such as granite. In the belt of weathering it decays; the complex minerals such as feldspar and mica are changed into simpler chemical compounds, and of these some are dissolved, while the remainder, with the unchanged quartz, forms soil. When carried away and assorted by water, this residue makes beds of sand and clay, and at the same time some of the dissolved substances are deposited as limy ooze. Thus far the process is *destructive.*

Gradually buried by more sediments, the sand, clay, and ooze come to lie in the belt of cementation and later in the zone of flowage. In the former they are consolidated, through the processes of cementing and crystallizing, into firm sandstone, shale, and limestone; in the latter, the simple minerals of which they are composed are mashed, recrystallized, and combined in the form of more complex minerals which together form solid crystalline rocks, in some respects not unlike the original granite. Here the change is *constructive.* If by still deeper burial the rocks could be heated to the melting point, they might actually be made over again into igneous rocks and thus complete the cycle. Whether this has occurred, however, is doubtful.

Questions

1. Figures 64 to 67 are maps on which the outcrops of the strata are shown as bands. The dip and strike are indicated by the usual sign. The beds are numbered in the order of their age, "1" being the oldest.

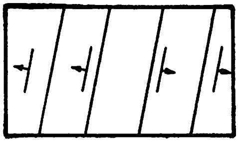

FIG. 64.

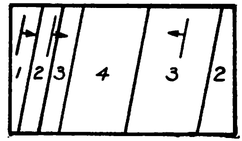

FIG. 65.

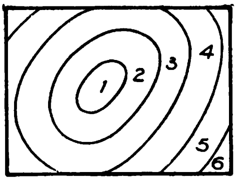

FIG. 66.

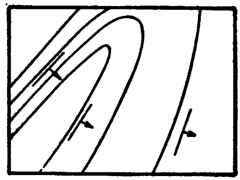

FIG. 67.

What structure in the rocks beneath is indicated by the observations in each case?

2. Show by sketch maps the surface of the outcrops corresponding to the beds shown in the cross sections (Figs. 68 to 71). Number the strata and show the dips.

FIG. 68.

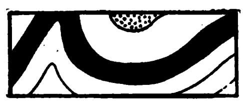

FIG. 69.

FIG. 70.

FIG. 71.

3. See Figures 45, 46, 47, 290, 291, and 414. Are the folds of the competent or the incompetent type?

4. Show by sketch maps how the outcrops may be changed by faulting along the lines represented in Figures 72, 73, and 74. Let the faults be normal and inclined toward the right in each case. Assume that the fault cliffs are cut down to a plain surface by erosion.

5. Explain the outcrops shown in Figure 75 and illustrate by diagrams.

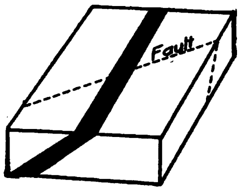

FIG. 72.

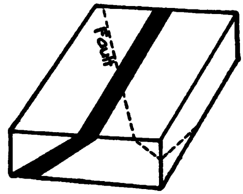

FIG. 73.

6. Why are reversed faults usually associated with folds? Why are the strikes of the two features usually parallel?

7. Why should normal faults be expected to disappear downward?

8. Why should earthquakes be more destructive to buildings situated on unconsolidated clay than to those on solid rock?

9. If of two springs in the same region, one is hot and the other cold, which may be supposed to have the deeper source?

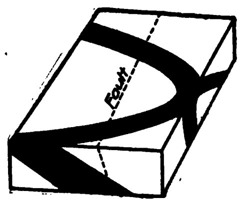

FIG. 74.

10. What phase of metamorphism is illustrated by the change of (1) gravel to conglomerate, (2) chalk to limestone, (3) peat to hard coal, (4) basalt to clay, (5) mud to slate?

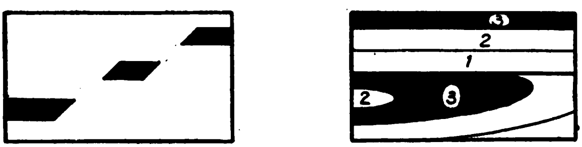

FIG. 75.

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CHAPTER III

THE WORK OF THE ATMOSPHERE

THE erosive effects of the atmosphere upon the surface of the land in general are less important than those of running water, because water is much heavier (over 800 times), and its work is concentrated for the most part along definite lines. Yet the atmosphere is an important geological agent because of its extreme mobility, and because two of its constituents, carbon dioxide and oxygen, by uniting chemically with many rocks, change their character and cause them to decay. The atmosphere is also indirectly of great importance. This is evident when it is remembered that without an atmosphere there would be no life upon the lands, no precipitation of rain or snow, and, in consequence of this, no work by streams and glaciers.

The work of the atmosphere may be considered under two main headings: (1) the work it accomplishes by mechanical means, and (2) that accomplished by chemical means.

MECHANICAL WORK

The mechanical work of the atmosphere is performed largely by the wind, and consists chiefly in transporting, wearing, and depositing rock materials. The atmosphere also influences the changes in rocks that are produced by variations in temperature.

TRANSPORTATION

Transportation by the wind is likely to be important wherever dry surfaces of fine material are exposed to strong winds. These conditions are fulfilled best over large areas in desert

and semiarid regions. When it is noted that desert regions cover about 11,500,000 square miles, or over one fifth of the land of the world, it is evident that the areas where wind work is of prime importance are by no means restricted. It is not apparent, furthermore, that desert areas are relatively more extensive now than at various times in the past, so that the wind has been a very important agent of change through long ages. Although it is most important in dry regions, the work of the wind is by no means confined to them. Rather is it world wide.

Material gets into the air in many ways. It is picked up by ascending air currents, given out by chimneys, stirred up along dusty roads by animals and vehicles, discharged by volcanoes, and delivered to the air in a variety of other ways. Once in the air, gravity tends to pull it back to the surface, but its fall is retarded by friction with the atmosphere. If the material is fine (dust), the surface it exposes to the friction of the air is great in proportion to its weight, and it settles very slowly. Before reaching the ground, it may encounter ascending currents and be carried up with them. When it falls again, it may meet and be lifted by other up-going currents, or may settle to the ground. Fine dust carried up to great elevations has sometimes remained in the air for many weeks at a time. After it reaches the surface, it may be moved repeatedly by the wind.

The amount of dust in the air at one time, even in moist regions, is often very great. In addition to vast numbers of larger dust particles, the air in many places (*e.g.* great cities) contains hundreds of thousands of invisible dust motes per cubic centimeter (about $\frac{3}{5}$ of a cubic inch). It has been estimated that in violent dust storms the air may contain as much as 126,000 tons of dust and sand per cubic mile.

Dust is transported great distances by the wind. It settles on ship deck in mid-ocean, has been carried from volcanoes to snow-capped mountains in distant parts of the world, where it was found subsequently, and in the exceptional case

of the eruption of Krakatoa in 1883, it was carried repeatedly around the earth in diminishing amount, its progress being recorded by the brilliant sunsets which it occasioned. It has, indeed, been suggested that every place upon the surface of the earth may possibly have dust brought by the wind from every other place upon the land.

Much wind-transported material settles upon the oceans. The aggregate effect of wind transportation is therefore to lower the lands and to raise the ocean floors, and this has been the case since the continents and oceans were formed. Although the result is insignificant within any short period, it is doubtless important in the long ages.

Fine material is carried higher and farther by the wind than coarse material, and it settles upon the surface more evenly, rarely forming surface features. Sand, on the other hand, is rolled and dragged along the ground, or lifted but a few feet above it, and therefore encounters many obstacles, such as trees, fences, buildings, and the like, about which it may lodge to form hills or mounds.

FIG. 76. — Telegraph pole near Palm Springs Station, southern California, deeply cut by wind-driven sand. The stones have been placed about the bottom of the pole to protect it so far as possible from the sand. (Mendenhall, *U.S. Geol. Surv.*)

ABRASION

How accomplished. — Wind of itself can do little or nothing in the way of wearing solid rocks, but the sand particles it often carries serve as effective tools which cut and wear the surfaces against which they are driven. The wearing power of wind-blown sand may be illustrated in various ways. It is shown by the artificial sand blast, a process in which glass is etched by sand driven against it with force. The glass in car windows has been destroyed

in a single day in passing through severe sand storms. In many places telegraph poles must be protected, or the wind cuts them down in a comparatively short time (Fig. 76). Wind wear (*abrasion*), like wind transportation, is most important in dry regions, for in such places slopes are often bare and unprotected, and the winds, frequently strong, are likely to be abundantly supplied with tools.

FIG. 77. — Wind-worn surface in Wyoming. The protruding masses are harder than the rock which surrounds them.
Why are these rocks not etched like those of Figure 78?

Characteristics of wind-worn surfaces. — The details of wind-worn surfaces depend on the strength and structure of the rocks. Rocks of varying strength wear unequally (Fig. 77), and often in the case of stratified rocks the more rapid removal of the weaker layers or laminæ leaves the stronger ones in relief (Fig. 78). Horizontal beds in deserts may be eroded into extensive flat-topped elevations, which are later cut up into abrupt conical hills, and finally destroyed. Inclined beds (whether worn by wind or water) tend to develop hills having a relatively long and gentle slope in the direction in which the beds dip, and a shorter and steeper opposite facing slope. Wind-abraded elevations generally suffer most rapid wear near the bottom, in spite of the fact that the wind is retarded by friction with the surface of the ground and its blows thereby weakened, for many more tools are carried in the low-

FIG. 78. — Cross-bedded sandstone etched by the wind.

ermost few feet of air than in the more swiftly moving currents above. As a result, such elevations are often undercut, and have steep and even overhanging slopes. Small, isolated elevations may take on the form of great mushrooms. If the pedestal is worn through, the larger upper part falls, and may be worn away in turn. Wind-worn slopes are frequently characterized also by the absence of accumulations of angular fragments (*talus*) at their base (Why?). Hard, compact stones on wind-swept surfaces are sometimes given flat and highly polished faces.

Erosion in deserts. — The final result of erosion in an interior desert basin is the formation of a nearly level rock-floored plain, covered more or less generally but thinly with hard, gravelly waste, and surmounted here and there by elevations representing the most resistant portions of the beds that have been worn away. In the earlier stages of the production of such a plain, when the slopes of the basin are still steep, the work of intermittent desert streams and occasional floods is more important than that of the wind. It is to be noted that the driest regions of the world now and then receive sufficient rains to cause floods. In the later stages, however, streams become less important as the surface becomes more even, and the wind comes to play the leading rôle. Whirlwinds lift dust high into the air, where it is taken up by the upper currents and carried outside the desert area. Strong winds sweep sand across the basin floor, and, if the inclosing slopes are not too steep, carry it over the rim to outside regions. By the removal of its waste in these ways, the basin is slowly lowered. During the process the wind may scour out depressions where the rocks of the desert floor are weak, but such depressions cannot become deep, because of the inwash of waste from the surrounding higher ground by temporary streams born of occasional showers. Thus the streams serve as a check upon the winds, and, as indicated above, an old-age desert plain is nearly level. Wind-degraded plains of interior basins differ from normal old-age plains developed by running water

in regions draining to the sea, in that the latter cannot be worn below sea level (p. 139) while the former are independent of it. The two are alike in having nearly level surfaces, which are independent of the underlying rock structures. Old desert plains with rock floors are said to cover thousands of square miles in South Africa.

DEPOSITION

Formation of dunes. — It has already been pointed out (p. 88) that the deposition of dust by the wind rarely gives rise to topographic features of importance, while that of sand frequently does. Elevations of wind-deposited sand are *dunes*. Figure 79 shows how sand begins to accumulate

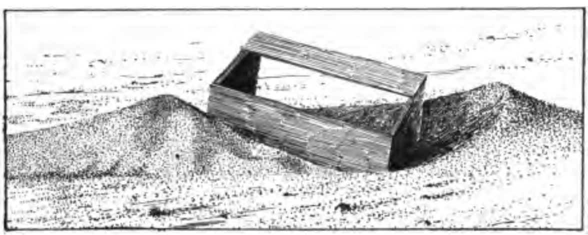

Fig. 79. — Sketch from photograph showing how sand accumulates about an obstacle which it cannot penetrate.

about an obstacle which it cannot penetrate. It is deposited on both the windward and leeward sides, but is prevented from resting directly against the obstacle by the air that is reflected from it, and by wind eddies. In the case of a penetrable obstacle, such as a hedge or open fence, the sand lodges chiefly on the leeward side (Fig. 80). Figure 81 shows sand beginning to gather in and about obstructing vegetation. Once started, a dune causes the lodgment of more sand, and so occasions its own growth.

Distribution, size, and shape of dunes. — Dunes occur chiefly along sea and lake shores, along sandy valleys, and in deserts; in a word, where quantities of bare, dry sand are ex-

posed to strong winds. They range in height from a foot or two up to 300 or 400 feet, and in rare cases even more. The great majority do not exceed 20 feet. In cross section they are typically as shown in Figure 82. The longer and gentler side faces the dominant wind, while the shorter and steeper side is the leeward slope. The windward slope is a roadway up which sand is rolled and dragged to the crest, behind which it drops. Its steepness varies with the strength of the wind, and the size and quantity of the sand. Strong winds are able to move a small amount of fine sand up relatively steep slopes; weak winds burdened with much coarse sand require a gentle grade. The leeward slope represents the angle at which the sand will rest, and rarely exceeds 24° or 26°. Dune sand is often distinctly, but irregularly, stratified (Fig. 83). Dunes vary in ground plan from roundish mounds and hills to elongate ridges. Examples of various types of dunes are shown on the topographic maps of Plate I.

FIG. 80. — Deposit of sand along the side of a fence.

FIG. 81. — Beginning of a dune on the beach of Lake Michigan, near Dune Park, Ind. Shows how sand accumulates about obstructing vegetation.

FIG. 82. — Cross section of a sand dune.

In order to read topographic or contour-line maps, it is necessary to know that contours are lines drawn on maps to express

relief (inequalities of surface), and that any given line runs through points of the same elevation above sea level. This will be understood readily by reference to Figures 84 and 85. Figure 84 shows a model of an ideal landscape viewed from above, on which lines have been drawn connecting places of equal elevation. In Figure 85 the above lines are shown alone; this is a contour map of the region represented by the model. By comparison of the model and map it will be seen that where the slopes of the former are steep,

FIG. 83. — Stratification in a sand dune near the head of Lake Michigan. (Bastin.)

the lines of the latter are close together, and *vice versa*. The vertical distance between two adjacent contour lines is the *contour interval*. The contour interval varies on different maps. In regions of low relief an interval of 10 or 20 feet is used frequently; in mountainous areas an interval of 500 or more feet sometimes has to be used in order to avoid having the lines too close together to be read. In the map of Figure 85 the interval is 20 feet, the exact value of the 100 and 200 foot lines being indicated. By counting the lines it will be seen that the top of the hill to the left of the river is over 260 feet above the level of the ocean in the foreground. It cannot be 280 feet high, however, for no 280 foot line is drawn. A comparison of the model and map will show also how valley depressions are shown by contours.

The features shown upon the three-color contour maps are of three general classes: (1) elevations and irregularities of the surface, shown by brown contours; (2) water, including streams, ponds, lakes, etc., represented in blue; (3) artificial features, such

as roads, railroads, towns, boundary lines, and the like, indicated in black.

FIG. 84. — Model of ideal landscape. (*U.S. Geol. Surv.*)

FIG. 85. — Topographic map of ideal landscape. (*U.S. Geol. Surv.*)

Migration of dunes. — If winds strike the base of a dune with less than they are able to carry, as happens frequently, they pick up sand from the dune surface and move it toward or to the crest, beyond which it falls. By this transfer of sand

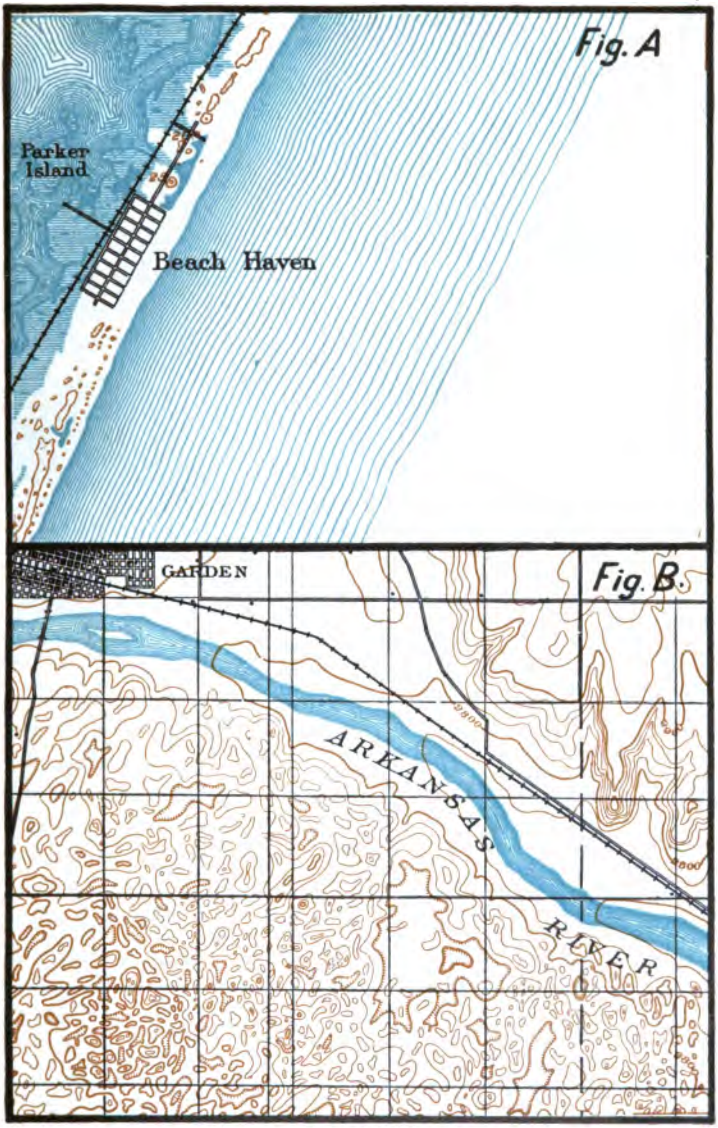

PLATE I. Fig. A. Dunes on the Coast of New Jersey. Contour interval, 10 feet. Scale, about 1 mile per inch. (Long Beach, New Jersey, Sheet, *U.S. Geological Survey.*) Fig. B. Dunes along the Arkansas River in Southwestern Kansas. Contour interval, 20 feet. Scale, about 2 miles per inch. (Garden, Kansas, Sheet, *U.S. Geological Survey.*)

from their windward to their leeward sides, dunes shift slowly in position (Fig. 86). From the nature of the migration it is apparent that only an extremely small fraction of the sand is in motion at any given time. Dunes have often invaded and destroyed farm lands and forests (Fig. 87), and have sometimes buried towns. The easiest and surest method of stopping migrating dunes is to plant vegetation upon them (Fig. 88). This fastens the sand and protects it from the wind.

FIG. 86. — Diagram showing successive positions of a migrating sand dune.

Topography of dune areas. — Figures 89, 90, and 91 show typical dune topographies. Depressions are sometimes as characteristic of dune areas as are the elevations (Fig. *B*, Plate I; depressions shown by hachures within closed contours), and are formed in a variety of ways. They may be scooped out by the wind. More sand may be deposited around than on a given place, which therefore forms a depression. Shifting dunes may fill parts of valleys, whose

FIG. 87. — Dune advancing upon a forest. Dune Park, Ind. (Cowles.)

FIG. 88. — Planting beach grass to stop the drifting of sand. Near Provincetown, Mass. (*U.S. Dept. Agr.*)

FIG. 89. — A group of dunes west of Mammoth Station, southeastern California. (Mendenhall, *U.S. Geol. Surv.*)

unfilled portions become depressions without outlets. Such depressions may be occupied by marshes and temporary ponds and lakes.

Taking the world as a whole, the amount of sand deposited by the wind, but not forming distinct elevations, probably far exceeds that in dunes.

FIG. 90. — Dunes in Colorado Desert, Cal. (Fairbanks.)

Eolian sandstone. — Wind-laid sand may be cemented into sandstone, though this is less likely to occur than in the case of water-laid sand (Why?). Sand subjected to long-continued action by the wind consists chiefly of quartz, for the softer minerals have usually been reduced to dust and blown away. The sand grains have often been worn to small size. Water-laid sand is carried in suspension more or less, and so subjected to less wear; its particles are therefore likely to be larger. Its composition, too, is more often mixed. The origin of a sandstone may be revealed also by its bedding, by the fossils it contains, and in other ways. It has been possible to determine that the sand of even very ancient sandstones was deposited by the wind.

FIG. 91. — Dunes on the coast of northern Denmark. (Engsig.)

Loess. — The wind has been concerned in the deposition in certain regions of *loess*. This is a silt, often buff-colored, that is intermediate in coarseness between sand and clay, and whose particles are remarkably uniform in size. Extensive

deposits of loess occur in the Mississippi Basin, in parts of Europe, and in China (Fig. 92), where in places it reaches a thickness of hundreds of feet. In this country, at least, some of the lowland loess appears to have been deposited in part

FIG. 92. — Loess deposit in Shan-si, China. The cañonlike cut followed by the road has been developed by the wear of traffic and wind. Two old levels of the road are shown above the one in use. The view shows the ability of loess to stand in steep walls. (Willis, *Carnegie Institution.*)

by streams, but the more typical upland loess was probably deposited by the wind. Loess soils are of great fertility where moisture is sufficient.

THE ATMOSPHERE AND ROCK BREAKING

Since changes in temperature are conditioned by the atmosphere, their effects upon rocks are considered here. When water freezes, it expands about one tenth of its volume. In doing so it exerts great force, as shown by the bursting of strong pipes by water freezing in them. When water which nearly fills rock cavities freezes, it may pry and break off pieces, and it may form and enlarge cracks. All unobtrusive processes by which exposed rock surfaces break up or decay are processes of *weathering*. Weathering by the wedge work of ice is obviously favored by many thawings and freezings. For the maximum of weathering by this process, it is desirable that the ice, having exerted great pressure upon the rocks in forming, should melt promptly, so that the water may penetrate farther into the enlarged cavities, and then freeze again. Accordingly, the wedge work of ice is in general most important in early and late winter, in moist regions that are situated in high middle latitudes. In very low latitudes temperature changes never involve the freezing point, except at high altitudes, while in very high latitudes the temperature may be below the freezing point for weeks or months, continuously.

FIG. 93. — Exfoliation of a granite bowlder. (Hole.)

Changes in temperature help to break rocks in another way. Rocks expand when heated and contract when cooled. Since they are poor conductors of heat, it is their surfaces which are not only first, but most affected by changes in

temperature. Under the heat of day the more rapidly expanding surface accordingly becomes too large to fit the interior, and with the fall of temperature in late afternoon and night

Fig. 94. — Exfoliate weathering in granite. Alabama Hills, Owens Valley, Cal. (Trowbridge.)

the surface layer becomes too small for the less rapidly shrinking rock beneath. As a consequence, the surfaces of rocks often shell off (Figs. 93 and 94), the process being known as *exfolia-*

Fig. 95. — Summit of Pikes Peak, Colorado, showing broken character of the rock. (R. T. Chamberlin.)

tion. Rocks containing a number of minerals are more likely than others to be broken by changes in temperature, for the different minerals expand and contract at different rates, thus establishing strains within the rock. Great and frequent changes in the temperature of the rocks favor their breaking by this process, and these conditions are met best in dry rather than moist regions, in low rather than high latitudes, and at high rather than low altitudes. In deserts and on bare mountains, therefore, the process is important, and in many cases the latter are nearly covered by loose, angular fragments that have been broken in this manner from the rocks beneath (Fig. 95), above which sharp, serrated peaks sometimes rise (Figs. 96 and 97). Pieces of rock loosened from steep slopes in this, or other ways, accumulate at the bottom to form piles of talus (Fig. 98). Some of the mountains of the Great Basin region are buried knee-deep with talus.

FIG. 96. — Serrate mountain topography. Peaks of granite in the Sierra Nevadas, near Mount Whitney. (Trowbridge.)

FIG. 97. — Serrate mountain topography. Peaks in the Mont Blanc group of mountains. (Tairraz.)

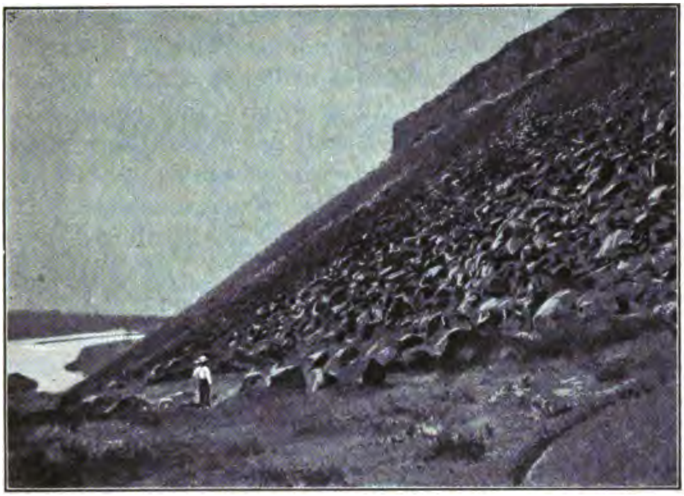

FIG. 98. — Talus slope in the Snake River Cañon, opposite Enterprise, Idaho. (Russell, *U.S. Geol. Surv.*)
What can be inferred from the picture concerning the character of the topbeds?

Chemical Work

The oxygen, carbon dioxide, and water vapor of the atmosphere are very active chemically. Chief among the rock substances with which oxygen unites is iron. This process (*oxidation*) is illustrated familiarly by the rusting of iron objects exposed in damp weather, the rust being a chemical combination of iron, oxygen, and water. The brick-red and yellow colors of many soils and rocks are due to the oxidized condition of their iron. Among the common minerals affected by the process are mica, hornblende, and augite, all complex silicates containing iron. The union of the carbon dioxide (CO_2) of the atmosphere with certain rock materials (*carbonation*), is also an important and common process. For example, carbon dioxide may unite with the calcium and with the iron of minerals containing these elements, to form calcium carbonate and iron carbonate. The chemical union of

the water vapor in the air, or of water after it has fallen as rain, with rock material, constitutes *hydration*.

Oxidation, carbonation, and hydration are all factors in the decay of rocks. All three involve an increase in the volume of the rock affected, and, unless something is withdrawn simultaneously in solution, the resulting pressure tends to make it crumble. The products of the changes, as in the cases of the iron and calcium carbonates mentioned above, may be soluble, and are likely to be carried away by waters percolating through the rock. Their withdrawal tends to increase the porosity of the rock, thereby weakening it. One of the most important chemical reactions attending the decay of igneous rocks is that by which orthoclase, acted upon by water and carbon dioxide, yields kaolin (p. 22). It may be expressed as follows:

$$\text{Orthoclase} + \text{Water} + \text{Carbon dioxide} = \text{Kaolin} + \text{Potassium Carbonate} + \text{Quartz}.$$

$$2\,KAlSi_3O_8 + 2\,H_2O + CO_2 = H_4Al_2Si_2O_9 + K_2CO_3 + 4\,SiO_2.$$

SUMMARY

The most important phases of the geological work of the atmosphere are the following: (1) Its work as an agent of weathering. Through its effect upon changes in temperature it influences (*a*) the wedge work of ice, and (*b*) the splitting of rocks by their expansion and contraction. The oxygen, carbon dioxide, and water vapor of the air unite chemically with various rock substances, and, by so doing, contribute to their decay. These processes prepare materials for removal by various transporting agencies. (2) The transportation and deposition of fine material by the wind. Although most extensive in arid regions, this work has affected, first and last, all land surfaces. Its aggregate effect is to lower the lands and build up the ocean bottoms. (3) The abrasion of rocks. This is most important in deserts, where the atmosphere is often the chief agent of degradation. (4) By controlling the conditions of evaporation and precipitation, the atmosphere

makes possible the work of streams and of glaciers, and the existence of land life.

Questions

1. On which side of Lake Michigan should dunes be best developed? Why?

2. Why are the most extensive dune areas of the Sahara in its western portion?

3. On which side of an east and west mountain range in the northern hemisphere should rock splitting due to temperature changes be most important? Why?

4. Compare and contrast the importance of rock splitting by temperature changes at Chicago and Denver, making clear the reasons for the differences.

5. Describe the sequence of events recorded by Figure 99.

FIG. 99. — View on South Manitou Island, Lake Michigan. (Russell, *U.S. Geol. Surv.*)

6. Why would it be of value to coat with tar the bottoms of telegraph poles in arid regions? Why coat only the bottoms?

7. How would a considerable increase in moisture change the geological processes in operation in the Sahara?

8. How might depressions made by the wind be distinguished from depressions made by rivers?

9. Why are some wind-swept rock surfaces smooth, while others are minutely pitted?

10. Indicate three ways in which the wind might form mounds such as those shown in Figure 100.

Fig. 100. — Mounds near Iron Mountain, Oregon, due to the work of the wind. (Russell, *U.S. Geol. Surv.*)

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CHAPTER IV

THE WORK OF WATERS UNDERGROUND

Facts about Ground Water

When a well, mine, or other opening of sufficient depth is made in the ground, water seeps into it from the surrounding rocks. The existence of water beneath the surface (*ground water*) is also proved in a simple way by the fact that it issues from the ground to form great numbers of springs in all humid regions, and occasional ones even in very dry regions. By digging deep enough it is possible almost anywhere to reach a level where the rocks are saturated with water. The level below which the rocks are full of water is the *level of ground water*, or the *water table*.

Source of ground water. — The ground water is related intimately to the rainfall, for water stands higher in wells in rainy seasons than in periods of drought, and springs are more numerous and of greater volume after plentiful rains than during periods of dry weather. Indeed, no other source exists from which important contributions to the ground water can be made. Most of the water beneath the ground therefore probably once fell as rain.

Proportion of the rainfall which enters the ground. — A portion of the water which falls as rain runs directly off the surface (*the immediate run-off*), another part is evaporated, and a third sinks into the ground. The proportion of the rainfall which enters the ground varies at different points and at different times, with (1) the slope of the ground, (2) the porosity of the soil and rocks, (3) the amount of water already in the rocks, (4) the rate of precipitation,

(5) the amount and character of vegetation upon the surface, and for other less important reasons. The greater the slope of the surface, the larger the proportion of the rain which joins the run-off, and the smaller the proportion, consequently, which enters the ground. If the spaces between the rock particles are large, as in sand or gravel, more water sinks into the ground than when the surface material is dense and compact, like clay. If the rocks are already nearly or quite full of water, little or no more can enter. After the surface material is filled with water, no more can enter until that within sinks out of its way. Meanwhile, all the water that falls is disposed of in some other manner. Other things equal, therefore, most water sinks into the ground when the downfall is gentle. This fact is in part responsible for the familiar statement that gentle rains are more beneficial to crops than heavy downpours. The run-off is greater from bare slopes than from slopes clothed with vegetation; in the latter case, accordingly, a greater proportion of the rain sinks below the surface. This fact is a fundamental consideration in connection with the recent agitation in favor of forest reserves about the sources of rivers which afford navigation or water power. With such forests a larger proportion of the rainfall sinks beneath the surface, later to issue gradually as seepage and springs, and so maintain the volume of the rivers throughout the year. Without them, the water from spring rains and melting snows flows away quickly, often causing destructive floods, and leaves the rivers with greatly diminished volume in the dry season.

The ground water at any given place is not dependent entirely upon local rainfall, for, as noted below, water often flows great distances underground.

Depth to which ground water descends. — From what has preceded, it is evident that water must fill the cavities in the rocks from the water table down as far as openings exist. As already indicated (p. 77), this is believed to be to a distance of five or six miles only, for at some such depth

all spaces, however small, are closed by the tremendous weight of the overlying rocks.

The temperature of the rocks, and therefore of the ground water, increases with the depth. The rate of increase varies in different places from one degree for about 17 feet of descent to one degree for over 100 feet. The larger figure is probably much nearer the average than the smaller one.

Amount of ground water. — If the average distance from the water table to the base of the zone of fracture were known definitely, and if, in addition, it were possible to determine what proportion of the volume of the rocks between is made up of cracks, pores, etc., it would be possible also to determine accurately the total amount of the ground water. It is sufficient to form a layer of water over the surface of the earth, having a depth estimated variously at from 800 feet, and less,[1] to 3500 feet, and more. The larger figure would represent only about one third, and the smaller figure but a small fraction of the water of the oceans. The ground waters encircle the earth, forming a rude sphere. The name applied to the waters of the earth, the *hydrosphere*, is accordingly an appropriate one.

Form and position of the water table. — The water table is not a level surface. If the rocks beneath an uneven surface such as that shown in Figure 101 were filled with water by rains, the water table would, of course, coincide with the surface of the ground, and would be far from level. Subsequently, the water would move under gravity from the higher levels *A* and *B* toward the neighboring lower levels. The ultimate tendency would be to make the ground-water surface level. The movement of the water would, however,

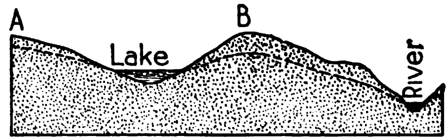

FIG. 101. — Diagram showing the relation of the level of ground water (the broken line) to the surface of the ground and to a lake and river.

[1] One of the latest estimates fixes the depth at only 96 feet.

be extremely slow, because of the small passages through which it must move and the friction it would develop with the rocks. Long before the surface of the water became level, further rains would be likely to raise it again beneath the uplands. In keeping with these considerations, the water table is found to repeat, in a general way, the topography of the surface above. As Figure 101 suggests, however, it is nearer the surface below the valley bottoms than it is beneath the hilltops.

As implied in the preceding paragraph, the position of the water table varies not only from place to place, but also from time to time at any given place. It is higher after heavy rains, and lower during periods of drought.

How ground water is disposed of. — On the average the amount of water withdrawn from the ground in the course of a year probably balances that which enters. It is withdrawn in various ways. It issues as springs and as seepage, is pumped out through wells, flows underground to the sea, is taken up by plants, and evaporates into the air which fills the rock cavities above the water table. It sometimes enters into chemical combination with rocks (pp. 103–104). The deeper water is probably imprisoned underground for long periods.

Springs and Underground Circulation

Kinds of springs. — When water issues from the ground in volume sufficient to form a distinct current, it constitutes a *spring*. When it issues in less quantity, it is known as *seepage*. Springs differ in many respects, and these differences have led to numerous classifications. Thus there are hot (*thermal*) and cold springs, intermittent and constant springs, deep and shallow springs, and many others. *Medicinal springs* are those whose waters have real or supposed medicinal value. The springs at Saratoga Springs, New York; Hot Springs, Arkansas; Vichy, in central France; and Karlsbad, in Bohemia, are famous examples. These

cities grew up largely or wholly because of the value of their medicinal waters. In general, the waters of *mineral springs* either contain large quantities of mineral matter in solution, or something which is striking because of its taste or odor. Most medicinal springs are mineral springs, but the reverse is not true. In 1908 there were 695 commercial mineral springs in the United States, which sold 56,108,820 gallons of mineral waters, valued at $7,287,269.

Among the more common deposits of springs are lime carbonate by *calcareous springs,* and iron compounds by *ferruginous springs.* Silica, gypsum, and many other things are also deposited by springs. Limestone is deposited by springs at San Filippo, in Tuscany, at the rate of one foot in four months, and has formed a mass 250 feet thick, a mile and a quarter long, and a third of a mile wide. Each year the springs at Bath, England, discharge, on the average, mineral matter sufficient to cover an area of 11,340 square feet with a layer one foot deep. A spring near Minden, Germany, has been found to bring to the surface each year salt enough to form a solid cube measuring 72 feet on a side.

Hillside springs, flowing wells, deep-seated springs, and *geysers* are types of springs which may be discussed briefly.

Hillside springs. — Figure 102 illustrates the occurrence of the ordinary hillside spring. If the upper (*P*) material is relatively porous (for example, sand), while the lower (*I*) material is relatively impervious (like clay), rain water will penetrate readily to the sloping surface of the impervious beds, along which it will flow slowly, and issue as springs at the base of the hill. The great majority of springs are of this class. They are usually not of great volume.

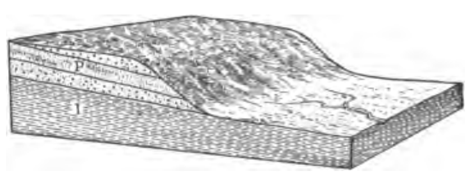

FIG. 102. — Diagram showing conditions for ordinary hillside springs.

Flowing wells. — These are artificial springs, and were formerly called *artesian wells,* from a province in France (Artois), where the first ones were dug. Any very deep well is now called an artesian well, even though its water has to be pumped to the surface. The conditions necessary for the formation of flowing wells are shown in Figure 103. They are: (1) a porous, water-carrying layer (A), which outcrops at a level (B) higher than that of the mouths of the wells; (2) rainfall sufficient to keep the porous layer well filled with water; (3) an impervious layer (C) above the porous layer. This confines to the latter the major part of the water which enters it at B. If under these conditions wells are sunk to the porous layer as indicated, the water at the points tapped, which is under the pressure of a sloping stratum of water which fills the cavities of the porous layer and reaches to the water table near B, will be forced through the openings to the surface, forming flowing wells. If a boring is made too far from the water table near the outcrop of the porous layer, the loss of force by friction between the water and the rocks through

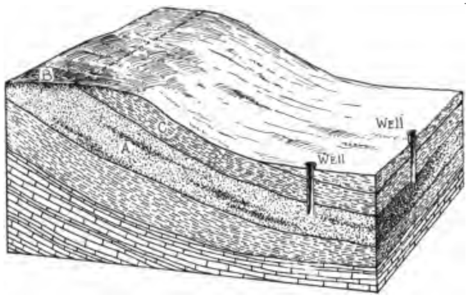

FIG. 103. — Diagram illustrating the conditions necessary for an artesian well.


FIG. 104. — An artesian well at Lynch, Neb. Flows more than 3000 gallons per minute. (Darton, *U.S. Geol. Surv.*)

which it passes will come to equalize the pressure of the water column, and no outflow will occur. Figure 104 shows a typical flowing well of large volume.

Artesian wells are common in parts of the Atlantic Coastal Plain, the Great Plains, southern Wisconsin, northern Illinois, and in many other places. Many cities such as Savannah, Georgia, and Brooklyn, New York, whose wells have a capacity of about 22,000,000 gallons per day, receive much water supply from artesian wells. In parts of the West, artesian waters are used extensively for irrigation purposes.

Deep-seated springs. — Ground water ascends to the surface from relatively great depths through large cracks or fissures in the rocks. It rises by hydrostatic pressure, as in the case of flowing wells. Figure 105 illustrates the occurrence of a deep-seated spring and suggests the intricate courses through joints and other cracks that water which descends to considerable depths must follow before completing its underground circulation. It moves down rather readily through the surface rocks, but as it descends deeper the pressure of the column of water behind it may force it toward the surface through any openings it encounters which lead upward. Sinking again through other cracks, it may follow a zigzag lateral course for a long distance, moving repeatedly up and down before reaching at last a fissure or other trunk channel through which it may rise to the surface.

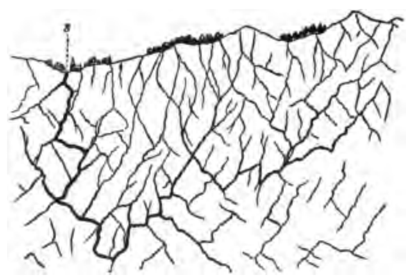

FIG. 105. — Diagram showing the intricate underground drainage which issues in a deep-seated spring. (Geikie.)

Geysers. — Geysers are hot springs that erupt at intervals. Existing geysers are confined to areas of recent volcanic activity in Yellowstone Park, Iceland, and New Zealand.

At irregular intervals the expansion of steam formed at some point below the surface of the water of the geyser, supposedly by contact with hot volcanic rocks, forces the overlying column of water into the air, like a great fountain. As the lava which heats the water cools, eruptions become less and less frequent, and finally cease. All existing geysers will therefore become extinct. They may, however, be replaced by others elsewhere.

The Work of Ground Water

Mechanical work. — In general, ground water transports very little material in a solid state, and this material wears

Fig. 106. — Shows the results of creep. The bare rock is sandstone, resting on a sloping surface of shale which is often made wet and more or less slippery by water sinking through the joints and other openings of the rocks above. The detached mass of sandstone has slowly settled away from the rock wall on the left, the line of division being determined by a large joint plane.

the rock surfaces it encounters but slightly. This is because ground water is rarely concentrated in well-defined channels to form streams, but usually moves very slowly (a few feet

a day) and at any given point, in small volume. By making the rocks which it saturates heavier and sometimes slippery, ground water often assists gravity in moving material, sometimes masses of great size, down slopes. When the movement is too slow to be seen, it is called *creep* (Figs. 106 and 107), when sudden, a *landslide* or *slump* (Figs. 108 and 109). When slopes are of unprotected clay, ground water influences creep as follows. As the surface clay dries after rains, it shrinks and cracks, forming sun cracks. The opening of a horizontal crack is largely the result of the down-slope movement of the clay below, rather than the up-slope movement of that above, for gravity assists downward movement, while it opposes movement up-slope. With the first shower the clay swells and the crack is closed. Under the influence of gravity it is closed chiefly from above rather than from below. Repeated shrinking and swelling mean very slow movement down slope. Other factors besides ground water are involved with gravity in creep. For example, rock fragments on a slope expand under the heat of day, and, because of the influence of gravity, the expansion is chiefly downward. When the fragments cool, they contract, and largely from their up-slope ends, since this again involves movement with, rather than against, gravity. The result of

FIG. 107. — The side of a ravine near Crawfordsville, Ind., showing trees leaning down-slope, in part because of creep. The surface material creeps faster than that at a slight depth, tipping the trees toward the axis of the ravine. (*Forestry and Irrigation.*)

many expansions and contractions is an appreciable movement toward the base of the slope. Landslides, too, may be due to a combination of causes. Rock masses may be in an unstable condition, and traversed by fissures and joint planes in such a manner as to favor landslides. Among other things, earthquake tremors and sudden and considerable changes in temperature (especially if they involve the

Fig. 108. — Landslide in the San Juan Mountains, Colo. (Howe, *U.S. Geol. Surv.*)

freezing point) may determine the moment when such masses slump.

Although the mechanical work of ground water is relatively unimportant, it does a vast amount of chemical work of several sorts, to which attention is now directed.

Solution by ground water. — Pure water dissolves only a few minerals and rocks readily, but practically all ground waters are impure. In general, water dissolves mineral matter more easily when its temperature is high rather than low, and when it is under great, rather than little, pressure. Its power to dissolve certain rock material is also increased

greatly when it contains carbon dioxide dissolved from the air, and to some extent when it contains matter derived from decaying vegetation. Since temperature and pressure increase with depth, it might at first thought appear that solution by ground waters should be most important near the base of the zone of fracture. It is evident, however, that for the continuation of this work there must be active circulation of the water; water charged with mineral matter in solution must be withdrawn to make room for other water able to dissolve more. As indicated on page 80, the *zone of greatest solution* is accordingly near the surface, where circulation is most active. Below this the dominant thing is deposition, rather than solution. It is, of course, not to be inferred that no solution occurs in the lower zone of deposition, or that deposition does not occur in the zone of solution.

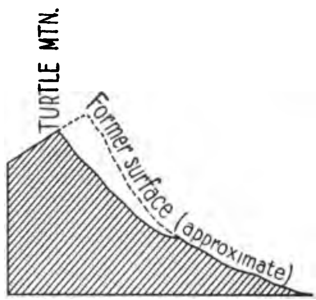

FIG. 109. — Profile of Turtle Mountain, Alberta, showing the amount of material removed in the Frank landslide of Apr. 29, 1903. A mass of rock nearly half a mile square and some 400 to 500 feet thick in places broke suddenly from the east face of the mountain and descended with great violence to the valley below, destroying part of the town of Frank.

Rocks are made porous and weakened by the withdrawal in solution of their soluble constituents, and solution is one of the most important processes in the weathering of rocks. Thus, if its cement be removed in solution, sandstone crumbles into sand, and conglomerate into gravel. Carbonated ground water (water containing carbon dioxide) sometimes removes so much limestone in solution from a given place that a cave or cavern is formed (Fig. 110). Such caves are common in parts of Kentucky and Indiana. There are said to be over 100,000 miles of underground chambers in the limestone rocks of the former state. The thinned and weakened roofs of caverns may fall in, forming surface

depressions called *sinks*. Sinks are often formed, however, without the collapse of cavern roofs. Many are funnel-shaped depressions dissolved in the rocks, through which water runs down into a joint, which may lead to a cavern (Fig. 110). If the two ends of a roof collapse, while the middle portion remains, the latter constitutes a *natural bridge*. Natural bridges are also formed in other ways (p. 244). In Karst, on the eastern side of the Adriatic Sea, the limestone rocks are so honeycombed by tunnels and openings dissolved out by ground waters, that much of the

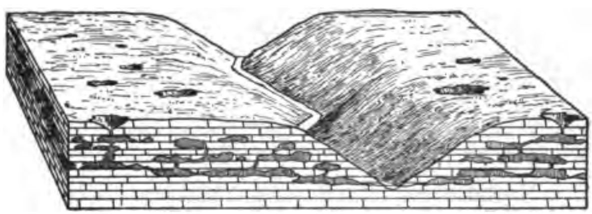

FIG. 110. — Diagram of caverns and sinks.

drainage is underground. Large sinks abound, some of them five or six hundred feet deep. Streamless valleys are common, and valleys containing streams often end abruptly where the latter plunge into underground tunnels and caverns, sometimes to reappear as great springs elsewhere. Irregular topography of this kind, developed by the solution of surface and ground waters, is known as *karst topography,* after the type region in Austria-Hungary.

Much of the material dissolved by the actively circulating ground water of the upper zone is sooner or later carried to the sea. It has been estimated that the rivers carry 4,975,000,000 tons of mineral matter to the sea in solution yearly, and most of this is contributed by ground water. It has also been calculated that the salt in solution in the sea would, if it were taken out of solution and deposited, form a layer 175 feet in thickness over the bottom, — that is, over nearly three fourths of the earth's surface. Most of

this, and in addition that contained in the waters of salt lakes and in the great salt deposits of certain rock formations, was obtained by ground water from rocks that contained the constituents of salt. Again, the great formations of limestone were formed either by the accumulation of the shells of marine animals that take lime carbonate from solution in the ocean water, or by precipitation from the overcharged waters of embayments or lagoons of the sea (p. 39). Most of the material of the limestone was dissolved by ground water from the rocks of the land and delivered to the streams, by which it was carried to the sea. These facts help to illustrate the importance of the work of solution done by ground water. The effect of the transfer of dissolved material to the sea is to lower the land. This is being accomplished by solution alone at an estimated average rate of one foot in about 13,000 years.

Deposition by ground water. — While possibly the major part of the mineral matter dissolved by ground water is carried in solution directly to the sea, vast quantities are deposited below and at the surface (p. 80). Deposition may be brought about in several ways. The water may be overcharged and deposit because of (1) evaporation, (2) a lowering of temperature, (3) a decrease in pressure, (4) a loss of part or all of the gas it contained, or (5) the mixing of waters having different things in solution. In the last case new combinations are likely to be formed, leaving the water overcharged with one or more things, which are deposited. Certain minute plants also have the power of extracting some things from solution. As already indicated, the *zone of greatest cementation* lies below the zone of solution, where the ground water is sluggish, and heavily charged with mineral matter.

Where material is deposited among loose rock particles, the latter may be cemented into firm rock (p. 37). Where deposition from solution occurs on the walls of cracks or fissures, the material forms mineral veins (Fig. 111). Most

of the copper, lead, zinc, iron, gold, and silver, occurring as veins or otherwise, was scattered widely through the neigh-

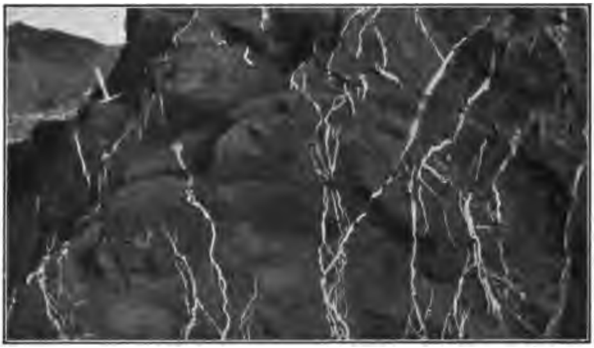

Fig. 111. — Calcite veins in volcanic tuff. West of Kincraig Point, Elie, Fife. (*H.M. Geol. Surv.*)

boring rocks, usually in the form of some compound, and was dissolved, concentrated, and deposited in its present position by percolating waters. Deposits made in caves are interesting, but of little importance. Those which extend downward from the roof, icicle fashion, are *stalactites;* those which are built upward from the floor are *stalagmites* (Fig. 112). In certain arid parts of the West, ground water ascends to the surface and is evaporated there, leaving the material which it held in solution as an incrustation which in places covers large areas.

Fig. 112. — Stalactites and Stalagmites in Marengo Cave, Ind. (*U.S. Geol. Surv.*)

Ground water some-

times dissolves material scattered through rocks and brings it together and deposits it in nodular masses. Such *concretions* (Fig. 113) are usually of material different from the dominant material of the rocks in which they occur. Thus, concretions in limestone are frequently of silica, and concretions in clay or shale are often of calcium carbonate or an iron compound. Concretions vary in form from nearly perfect spheres to nota-

Fig. 113. — Ironstone concretion in shale. South shore of Lake Huron, about 25 miles northeast of Sarnia, Ont. (Lee.)
How does the picture prove that the concretion was formed after the deposition of the shale?

bly irregular lumps and masses, and range in diameter from a fraction of an inch to 10 or 15 or more feet. A fossil sometimes forms the nucleus about which a concretion grows. While many concretions have been made after the formation of the inclosing rocks, others have developed during the deposition of the sediments. When concretions are made in soft sediments, they often press the surrounding material away as they grow.

Small cavities in rocks may be partly or wholly filled by material deposited from solution in ground water, forming

secretions. Cavities lined with inward-pointing crystals are *geodes.* Agates are also examples of secretions.

Other changes accomplished by ground water. — The shells of animals, trunks of trees, etc., which are buried in gathering sediments, may, as they decay, be carried away bit by bit by ground waters and be replaced by the deposition from solution of other mineral matter, often silica. The

Fig. 114. — Petrified logs in the petrified forest, near Adamana, Ariz. (Atwood.)

minutest structure of the wood, for example, is thus preserved in stone, and the wood is said to be *petrified* (Fig. 114). The process is called *petrifaction.* It has been of great importance in preserving in fossil form a record of past life. Replacement by ground waters has affected many kinds of rocks on a vast scale. Many concretions are made by the process of replacement.

As already pointed out (p. 104), ground water may enter into chemical combination with certain rock constituents. Hydration is a chief factor in the decay of rocks. Mineral matter in solution in percolating water may also form new chemical combinations with constituents of the rocks through which the water passes, and thus be locked up for long periods of time.

Importance of chemical work of ground water. — From the preceding paragraphs it is apparent that ground water may modify the character of rocks in several ways: (1) by removing soluble constituents; (2) by depositing new material in rock cavities; (3) by replacing old material with new; and (4) by forming new chemical combinations. The result is often to alter profoundly the character of the rocks affected. Thus water is one of the leading agents of metamorphism (p. 78). Furthermore, changes of the sort suggested above must have occurred on a vast scale, for ground waters have been at work throughout the zone of fracture for untold millions of years.

Questions

1. In order to contain water permanently, must wells be sunk deeper below the surface in valleys or on uplands?
2. Make a diagram showing (1) the position of the water table during the rainy and during the dry months, and (2) two wells, one of which goes dry at times, while the other always contains water.

Fig. 115. — An exposure of rocks in a railroad cut, Columbia, S. C. (Trowbridge.)

3. Describe the characteristics of a climate that should (1) favor, and (2) hinder, the work of solution by ground water.
4. Would caves be more likely to develop in limestone regions whose surfaces were well above or near to sea level?
5. Why cannot extensive caverns in a given region be formed

below the level of the bottom of the largest valley of the region? (See Fig. 110.)

6. In parts of eastern Tennessee sinks occur in belts that are rudely parallel to one another. What facts may be inferred from this concerning (1) the character, and (2) the structure, of the rocks?

7. What inferences may be made from the fact that on a given valley side strong springs occur at intervals along a line that rises down valley?

8. What facts concerning ground water are illustrated by Figure 115? What inferences may be made concerning the rocks?

9. What inferences concerning ground water may be made from the fact that at many points in the ocean near shore, strong fresh-water springs well up?

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CHAPTER V

THE WORK OF STREAMS

The run-off. — It is estimated that the total amount of rain which falls yearly on all the land is equal to about 35,000 cubic miles of water, enough to cover all New England more than half a mile deep. As indicated on page 107, a portion of this rain water sinks into the ground, a portion runs off over the surface, and a third part is evaporated. The immediate run-off, reënforced by the overflow of lakes, by contributions from springs and seepage and from melting snows, flows always from higher to lower levels. All that is not lost by evaporation or by sinking beneath the surface therefore runs ultimately to the sea. Streams are estimated to carry 6500 cubic miles of water (enough to cover Connecticut and Rhode Island more than a mile deep) to the sea each year. This water descends on the average nearly half a mile before reaching the ocean. During the descent a large but unknown amount of energy is used up as internal friction in flowing on low slopes, and as friction on the channels of the streams and on the sediment which the streams carry. In addition, an enormous amount of energy is exerted in geological work. The nature of this work and the results are discussed below.

The Processes of Erosion

The general term *erosion* covers those processes by which rock surfaces are worn and broken up, and the loosened material removed. It therefore includes *weathering*, *transportation*, and *corrasion*. By the last is meant the mechanical wearing of rocks, particularly by running water.

WEATHERING

Processes of weathering. — As earlier discussions have indicated, weathering is a term applied to nearly all the processes which cause rocks to break up and decay. From the standpoint of general erosion, weathering may be defined as *preparation for transportation,* for it reduces rocks to pieces sufficiently small to be blown or washed away. Furthermore, most of the material moved by wind and water was derived from bed rock in this way. The mantle rock and materials dissolved in the hydrosphere are the most important products of weathering. The principal processes of weathering were discussed in connection with the work of the atmosphere and of ground water (pp. 100–104, 117). Some of the remaining processes may be noted here. The mechanical beating of raindrops disturbs small surface particles and causes them to wear one another to slight extent. More important is the work done by plants and animals. The growth of roots in joints and other cracks of the rocks enlarges the openings, and by so doing not only helps directly to break the rocks, but increases the surface exposed to other weathering agents. Root splitting is illustrated by Figure 116. Burrowing animals make openings in the rocks, and in the aggregate bring large quantities of material to the surface, where it is exposed to the attack of the weather. Gravity is regarded usually as an agent of weathering. For

Fig. 116. — A tree growing in an opening in a rock. The growth of the tree has pried the parts of the rock apart, and enlarged the opening from a narrow crack to its present size. Lansing, Mich. (Macpherson.)

Fig. 117. — An example of unequal weathering. Granite bowlders have weathered out of an easily disintegrated formation. Just south of the Tropic of Cancer, on the Asiatic mainland opposite Hong Kong. (R. T. Chamberlin.)

the most part, however, it merely moves material already prepared for transportation by other agents down to lower levels.

Rate of weathering. — The rate at which weathering prepares material for removal varies greatly with (1) the character of the rock (Fig. 117), (2) the climate, and (3) the rate at which the waste already formed is removed. (1) Open-textured rocks with many joints and other cracks absorb

Fig. 118. — St. Peters Sandstone, eastern Iowa. Showing effects of joints and bedding planes upon weathering.

much water, and so favor the wedge work of ice, and, where some of the constituents of the rock are soluble, solution. Figures 118 and 119 illustrate the influence of joints upon the weathering of stratified rocks, and Figure 120 shows the effect of joints upon the weathering of granite. Dark objects heat and cool more rapidly than light ones, and dark rocks accordingly favor splitting through changes in temperature. (2) No single type of climate favors all the processes of weathering. It was seen on page 100 that the wedge work of ice is most important in moist regions where there are frequent changes in temperature which involve the freezing point. The chemical work of the atmosphere and of ground water is, on the other hand, most important in hot, moist climates. An arid climate with great daily range in temperature favors rock splitting, but opposes the work of plants, animals, and ground water. If rocks are not buried too deeply with soil and subsoil, they probably weather fastest, everything considered, in a hot and moist climate; but flat lands in regions having such climates usually have thick accumulations of mantle rock. It is said to reach a thickness of 300 feet or more in parts of Brazil. (3) If the products of weathering remain where formed, they finally cover the bed rock so deeply that it is more or less completely protected from further attack. If, on the other hand, they are removed as fast as

FIG. 119. — Limestone columns weathering away. The openings between the columns are enlarged joints. The surrounding rock has been removed by erosion. Eastern Iowa.

What are the various ways in which these rocks are being weathered? How may the preservation of these rocks after the removal of the surrounding rocks be explained?

formed, so that bare rock is always exposed, the work of ground water and of plants and animals is reduced greatly. It consequently follows that, other things equal, weathering

FIG. 120. — Weathered forms in granite, Laramie Hills, Wyo. Three sets of joints may be seen, and their influence upon the weathering of the rock is clearly evident.

proceeds most rapidly when its products are rather promptly, but only partially, removed.

The fact that over most of the surface of the land there is a mantle of soil and subsoil indicates that, in general, weathering exceeds transportation.

Questions

1. Does the absence of soil in any given place mean that weathering is not in progress there?
2. What are the principal agents of weathering in the Sahara? New York? Louisiana? The Amazon Valley?
3. Would a given stone wall stand longer in Labrador or in Florida? What are the principal agents of weathering by which it would be destroyed ultimately in each place?
4. What differences in weathering might reasonably be expected on the two sides of an east and west valley? On the two sides of a high north and south mountain range in the latitude of the United States? Of an east and west range?

5. **Flint nodules are of common occurrence in limestone (p. 121). Explain the fact that in certain limestone regions the stream beds contain few limestone bowlders, but many of flint.**

6. Why does residual mantle rock in many cases merge gradually into the firm rock beneath? (See Fig. 214.)

7. Describe and explain what you see in Figure 121.

FIG. 121. — Granite rocks. Laramie Hills, Wyo.

TRANSPORTATION BY STREAMS

Getting a load. — Streams roll and drag material along their beds, and carry it in mechanical suspension and in solution. That which is moved mechanically is obtained in a variety of ways. Streams wear material from their beds and banks, and remove that which is already loose. Sediment is brought in by tributaries. Material loosened by weathering on the tributary slopes is delivered to the stream by gravity or by rain wash. A certain amount of fine material is brought by the wind. Most of the material which is carried in solution is contributed by issuing ground waters; a small part is furnished by the unorganized run-off, and another minor portion is dissolved by streams from the rocks over which they flow.

How the load is carried.—A stream pushes sediment along its bottom by the direct impact of the current, and also rolls and drags it by the friction of the bottom water, some-

what as one might move sand grains on a table by dragging the outstretched hand across them. Material is held in suspension chiefly by minor up-moving currents. Since rock material is on the average two and one half to three times as heavy as the water it displaces, it tends, under gravity, to sink to the bottom. In standing water it sinks vertically. In a stream whose water is moving horizontally, two forces act upon it. Gravity, of course, seeks to draw it directly to the bottom (*G*, Fig. 122), while the current tends to move it in the direction of its flow (*C*, Fig. 122). The sediment accordingly follows a course (*S*, Fig. 122), which is a resultant of the combined forces. It reaches the bottom in the same time it would in standing water of the same depth. In nature, however, stream water rarely, if ever, moves horizontally for any distance. Bowlders and other irregularities on the bottom deflect portions of the main current obliquely upwards. Projections of the bank likewise create subordinate currents, some of which move upwards. Sediment settling to the bottom along an oblique path may encounter such up-going currents and be lifted by them. Presently sinking again, it may again be lifted or may reach the bottom, perhaps to be presently carried up once more by other upward currents. Material the size of sand, and larger, probably rarely makes extended trips in suspension; instead, many short trips are interrupted by periods when it rests upon the bottom, or is dragged and rolled along it. On the other hand, mud and silt are often carried long distances before settling. Nevertheless, even fine material probably normally requires thousands of years to make the trip from the sources of the larger rivers to their mouths, for it is dropped on the way many times for long periods, perhaps helping to form bars and

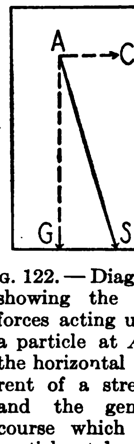


FIG. 122. — Diagram showing the two forces acting upon a particle at *A* in the horizontal current of a stream, and the general course which the particle takes in sinking to the bottom.

islands or being built into flood plains, from which it is removed later, to be carried another stage on its journey to the sea. Just as in the atmosphere (p. 87), material sinks more slowly in proportion as the surface it exposes to the friction of the water is great in relation to its weight. Sediment of a given sort settles faster in salt water than in fresh water.

The amount of the load. — The amount of the load which any given stream is moving depends upon (1) its velocity, (2) its volume, and (3) the amount and nature of the material to which it has access. Obviously, the swifter and larger a stream, the more and larger the material it is capable of moving. But many swift streams carry little material, because little loose material is available, or because it is in pieces too large to be moved. The Mississippi River carries on the average over 1,000,000 tons of sediment per day into the Gulf of Mexico. It has been calculated that it discharges sediment sufficient to fill the basin of Lake Superior, the largest lake in the world, with an area of 32,000 square miles and an average depth of 550 feet, in about 66,000 years. It has been estimated, also, that the work performed each year by the Missouri River in transporting sediment is equivalent to 275,000,000,000 mile tons, or tons carried one mile. The railroads of the United States carried 236,600,000,000 mile tons in 1907.

Questions

1. Why are many mountain streams clear?

2. Why in many streams are narrows in the channel floored with coarse material, while broad parts of the channel are lined with fine sediment?

3. Do two streams of the same velocity and volume necessarily carry the same amount of sediment? Reasons?

4. Can a given stream carry a greater weight of coarse or of fine material? Why?

5. (1) Just why do streams carry more sediment after heavy rains? (2) Would the effect of a given rain in northern United States be likely to be the same in January as in July? (3) Make a general statement concerning erosion, in keeping with the answer to (2).

CORRASION

How streams wear rock. — Like clear air, clear water can do little in the way of mechanically wearing firm rocks. Perhaps the most striking illustration of this is afforded at Niagara Falls. Seven thousand tons of essentially clear water rush over the brink of the falls each second, and yet certain

FIG. 123. — The tools of a river. Stream-worn pebbles in the bed of the Potomac River at Barnum, Md. (*Md. Geol. Surv.*)

tiny plants grow in the water, clinging to the rocks at the very edge. Were erosion actively in progress at the edge, the plants would, of course, be swept away. The St. Lawrence River leaves Lake Ontario as clear as the lake waters themselves, and for many miles is unable to corrade effectively, even where its current has great velocity and washes the shores of islands whose banks are of clay. Many other streams which flow from lakes illustrate the same thing. They often have mossy channels in spite of swift currents. Streams, like winds, wear rocks by means of the rock fragments which they transport (Fig. 123). Sand grains, pebbles, etc., that are swept along by the main current, rub, rasp, and strike the bed and sides, breaking and wearing pieces from them. Material

in suspension is also frequently driven vigorously against the bottom by subordinate downward-moving currents, with similar effect. The tools are themselves worn in the process. Stream-swept stones become rounded (Fig. 123), and their surfaces often have many tiny pits, or depressions, made by the blows they have delivered or received. These characteristics have helped to prove that the material of certain rock formations was handled by vigorous streams.

Rate of wear. — The rate at which degrading streams lower their channels depends on several conditions. (1) Weak rocks with soluble cements favor rapid wear, while strong, nonsoluble rocks retard it. Stratified rocks in general prove less resistant than massive rocks. Other things being equal, rocks with numerous joints and cracks are worn faster than others, because these openings are planes of weakness. (2) Rapid streams deal harder blows and more of them than slow ones, and so, other things being equal, wear their channels faster. The velocity of a stream, in turn, depends upon (*a*) the slope (*gradient*) of its channel, (*b*) its volume, (*c*) its load, and (*d*) the shape of its channel. Obviously, the steeper the channel and the larger the stream, the greater its velocity. Energy is expended in moving sediment, which otherwise would express itself in greater velocity; other things equal, a given stream accordingly flows fastest if clear, and slowest if loaded. A stream is retarded by friction with its bed and sides. Crooked channels, with wide, uneven bottoms, occasion great friction, and tend to produce a sluggish current; straight channels with narrow and smooth bottoms develop less friction, and promote greater velocity. (3) Since the velocity of a stream is decreased as its load is increased, it follows that the force of its blows is also diminished. In other words, the greater the number of tools carried, the greater the number of blows delivered in a given time, but the weaker each blow is; while, on the other hand, the fewer the tools carried, the fewer the blows delivered in a given time, but the stronger each blow becomes. Clearly, streams wear

fastest, other things being equal, when carrying a partial load, so that many blows are delivered, but not so many that all are weak. (What qualities should render rock fragments most efficient tools for stream corrasion? Would tools possessing these qualities long retain them all? Why?)

Graded streams. — When the gradient of a stream is just steep enough to give it the velocity necessary to wash forward the sediment brought to it from the tributary slopes, it is said to be at *grade*. If it is able to transport more than is delivered, it removes material from its bed until it comes to grade at a lower and gentler slope. If it is unable to transport all that is delivered, part of the load is left as a deposit. By this means the channel is raised and the gradient becomes steeper gradually, until in time the stream grows swift enough to carry away the sediment brought to it.

Rate of land reduction by stream erosion. — Estimates have been made of the rate at which certain river systems are degrading their basins. This may be done as follows: The width, average depth, and mean velocity of the main river at its mouth may be determined at different times by measurements, and from these data the average volume of water discharged per year may be calculated. The average amount of material contained in a cubic foot of the water, both in solid form and in solution, may also be learned by examination of numerous samples. Knowing the average amount of sediment in each cubic foot of the water, and the average number of cubic feet discharged in a year, the total amount of sediment delivered at the mouth of the river may be computed readily. Finally, the area of the drainage basin being known, one may determine to what uniform depth the sediment removed yearly would cover it. The result indicates the average rate per year at which the drainage basin is being degraded. By this general method it has been estimated, for example, that the Mississippi Basin is being lowered mechanically at the average rate of one foot in about 5000 years, and when the amount removed in solution is considered also, one foot in 3500

years. The Ganges Basin is being reduced by the removal of material in the solid form alone, at the rate of a foot in less than 2000 years; and the Danube Basin a foot in approximately 6800 years. In some parts of each basin the rate is far more rapid. Figure 124 shows the results of recent estimates of the rate of land reduction throughout the United States.

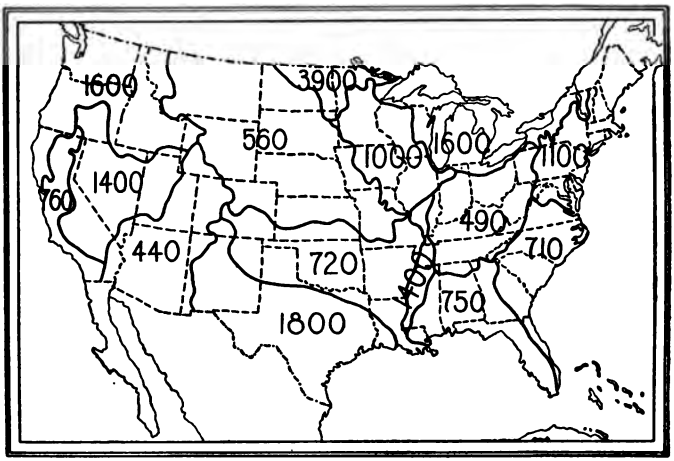


Fig. 124. — Rates of land reduction by stream erosion in the United States. The figures are the number of years required for one inch of denudation. (After *National Conservation Commission.*)

The average elevation of the continents above sea level is about 2300 feet. If they were being degraded by streams at the average rate of the Mississippi Basin, and continued to be cut down at that rate to sea level, and nothing occurred to offset the work of the streams, the lands would be destroyed in about 8,000,000 years. Probably, however, the average rate of land reduction is less than that assumed. Nor could the present rate, whatever it may be, continue till the land was at sea level, for as it gets lower, the streams would flow more slowly, and therefore degrade less rapidly. Again, judging by the past, diastrophism and vulcanism would intervene to maintain the land masses. Still other factors would modify

the problem, as, for example, the fact that streams cannot reduce their basins quite to sea level (p. 139) and that an average of 2300 feet would not have to be eroded away to bring the land to the level of the sea, for the surface of the ocean would be raised by the deposition in it of the waste from the land. Nevertheless, such computations are worth while, since they aid one to appreciate the importance of the work being done by running water.

Questions

1. Why is the Niagara River practically free from sediment?

2. Other things being equal, would a given stream corrade faster when flowing across the edges of highly tilted beds, or on horizontal beds? Why? When the beds dip downstream or upstream? Why?

3. Is corrasion favored more by a constant volume, or by great and sudden fluctuations in a stream?

4. Enumerate all the conditions which might enable one of two streams of equal and constant volume to corrade much faster than the other.

5. Is it possible for a stream to corrade without degrading? To degrade without corrading?

6. Will a given stream flow faster when fully loaded with coarse or with fine material?

Features Developed by River Erosion

VALLEYS

Most streams flow in valleys. In general, valleys correspond in size to their streams, and, like the stream it contains, a given valley is smaller than the one it joins, and larger than those which join it. At their union, the bottoms of tributary valleys are normally at the same level as the bottoms of the larger valleys to which they lead. Furthermore, all streams are engaged, with the help of the agents of weathering, in enlarging their valleys. These facts indicate that the valleys were not found ready-made by the streams which occupy them, but that they are a result of the work of the streams aided by weathering agents. Many synclinal troughs (p. 66) form valleylike depressions. Since they are due to the structure

of the rocks, such valleys are called *structural valleys.* They usually contain stream valleys in their bottoms.

FIG. 125. — Sketch of a gully.

The beginning of a valley. — Figure 125 shows an infant valley or *gully*, which contains running water only during rains. In the future, rain water running down the slope into the head of

FIG. 126. — Gullies near Riverside, Cal. (Fairbanks.)

the gully will make it longer; water coming over the sides will make it wider; and the water which flows along the bottom will make it deeper. Thus it may become sufficiently long and wide and deep to be called a *ravine*, and finally a valley. When its bottom is worn below the

FIG. 127. — A mountain ravine near Marshall, N. C. (*U.S. Geol. Surv.*)

water table, ground water will enter it as seepage and springs from the sides, and flow away as a stream. When the bottom of a valley is below the wet-weather level of the water table, but above the dry-weather level, it contains an *intermittent stream*, but when the bottom of the valley is eroded below the water table at its lowest level, the stream is permanent, and the enlargement of the valley proceeds without interruption. Figure 126 shows many gullies starting on an unprotected surface in a relatively dry region, while Figure 127 shows a mountain ravine in a humid region.

Valley deepening. — A stream lowers its channel, and so deepens its valley, by removing material loosened by weather-

FIG. 128. — A stream undercutting its bank and widening its valley. Central Illinois. (Crane.)

ing or by its own corrasion. But there is a limit below which a stream cannot degrade its valley flat. This is the level of the lake, sea, or other valley to which it leads. Furthermore, it can cut to this level only at its mouth, from which the valley bottom rises upstream, very gently in the case of large rivers, and more rapidly where the stream is small. For some distance above their mouths, streams may, however, cut their *channels* slightly below the level of the sea or lake into which they flow. The lowest level to which a stream can cut is

base level. As a stream approaches base level, it flows on a diminishing slope, and its current therefore becomes less and less rapid. In other words, a stream approaches base level more and more slowly as it draws nearer and nearer to it, so that the removal of the last few feet may take longer than all the rest.

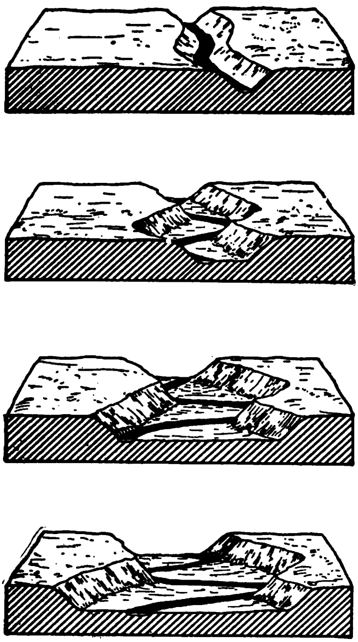


FIG. 129. — Diagrams of a river developing a flat by side cutting.

Valley widening. — Valleys are widened in a variety of ways. Relatively sluggish streams are pushed aside by the currents of their tributaries or by obstacles. In this way the stream is driven first against one bank, and then against the other, and so undermines each. The points of attack varying from time to time, the valley is opened generally, and a valley flat is developed (Figs. 128 and 129). Meanwhile, other agencies assist in widening the valley. Rains wash weathered material down its sides, and if the slopes are sufficiently steep, fragments also roll and fall down them. Material works its way down the sides of the valley also by creep and by slumping (p. 115), and is removed in other less important ways. If the material remained at the bottom, the effect would

FIG. 130. — The divide between the two valleys is being consumed by the side cutting of the rivers. It may be cut away entirely, in which case the two valleys will become one.

be to narrow the valley there, while widening it above. Usually, however, it is carried away by the stream. By the widening of two adjacent valleys, the intervening ridge may be worn out, the two becoming one (Fig. 130). The continuation of this process among neighboring valleys would ultimately reduce the entire surface of the area affected to the level of the valley bottoms.

Valley lengthening. — The heads of valleys are usually without permanent streams, for they are commonly above the lowest level of the ground-water surface. The stream, therefore, does not assist in the lengthening of its valley headward, but all the other agencies which widen valleys help also to lengthen them. A valley ceases to grow by headward erosion when a permanent *divide* (Fig. 131) is established. This is when the wear accomplished by the run-off which

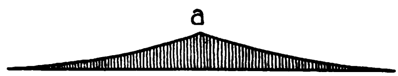


FIG. 131. — Diagram of a divide. The crest of the divide (at *a*) is permanent if the conditions of erosion are the same on the two sides. Rainfall may lower it, but it cannot shift its position horizontally.

FIG. 132. — Bad-land topography near Grand Junction, Colo. Shows many gullies. (Baker.)

enters the head of the valley is balanced by the erosion of the water which runs from the divide in the opposite direction. Thus limits are set to the growth of a valley in all three

dimensions. In depth, the limit is base level; in width and length it is fixed by neighboring valleys.

Struggle among valleys. — It is not to be inferred from what has preceded that all gullies become valleys, or even ravines. Quite the opposite is true. Few of the gullies shown in Figure 132, for example, can grow to ravinehood. As they widen, the intervening divides will be worn out, combining adjacent gullies and reducing the number. Many gullies are commonly destroyed in the formation of a single ravine, which in turn is likely to presently find its growth contested by other ravines. Such a conflict is shown in Plate II, among the ravines near Wesley. Little opportunity for growth remains to most of the ravines in the vicinity, and many are doomed to early destruction by their more powerful neighbors.

Valleys without gullies. — Not all valleys have grown from gullies as described above. In the northern part of the United States and in Canada, for example, thousands of lakes were formed during the Glacial period (p. 214). In the moist climate of this region, the lakes received more water as rain on their surfaces and as run-off from tributary slopes, than they lost by evaporation. Consequently, many overflowed their rims, forming streams. Such streams followed the lowest available lines of descent to other streams or lakes, and by erosion developed valleys. Thus the streams existed before the valleys. In this and other ways, streams and valleys of this class are in contrast with those considered first.

Tributary valleys. — Most valleys have tributaries, and these in turn branch repeatedly, like the limbs of a tree. A main valley and all its tributary valleys constitute a *valley system*, whose streams, the main river and all its branches, form a *river system*. The entire area drained by a river system is a *drainage basin*. Tributary valleys commonly start as gullies on the sides of their parent valleys. If the slope of the ground back from the sides of a valley is such that more water enters it at some points than at others, the velocity, and hence the erosive power, of the entering water will be

greater at such places than elsewhere, and tributary depressions (gullies) will result. Even if an equal amount of water entered the parent valley at all points, the same result would follow, provided the rocks of the valley sides were of unequal strength, for erosion would be more rapid where the rocks were weaker, giving rise to tributary depressions.

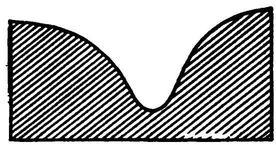


FIG. 133. — Cross section of a young valley.

Stages in topographic development. — It is apparent from the preceding paragraphs that valleys pass through careers just as men do. Each stage in the career of a valley is characterized by certain features, so that by observing the form of a given valley, one may determine readily what point it has reached in its development. Valleys are *young* when still narrow and steep-sided (Fig. 133). These features indicate that as yet down cutting is keeping ahead of other processes. Most young valleys have few and imperfectly developed tributaries and relatively steep gradients. (What things will determine whether or not young valleys are deep?) Young valleys in various stages of development are shown on Plate II. *Mature valleys* are wider, deeper, and have gentler gradients and more and larger tributaries. In

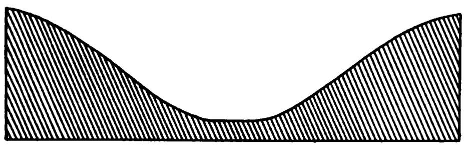


FIG. 134. — Cross section of a mature valley.

FIG. 135. — Cross section of an old valley.

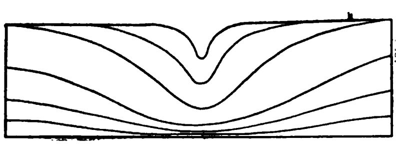


FIG. 136. — Diagram showing changes in the shape of a valley as it advances from youth to old age. The material in which the valley is cut is all of the same character.

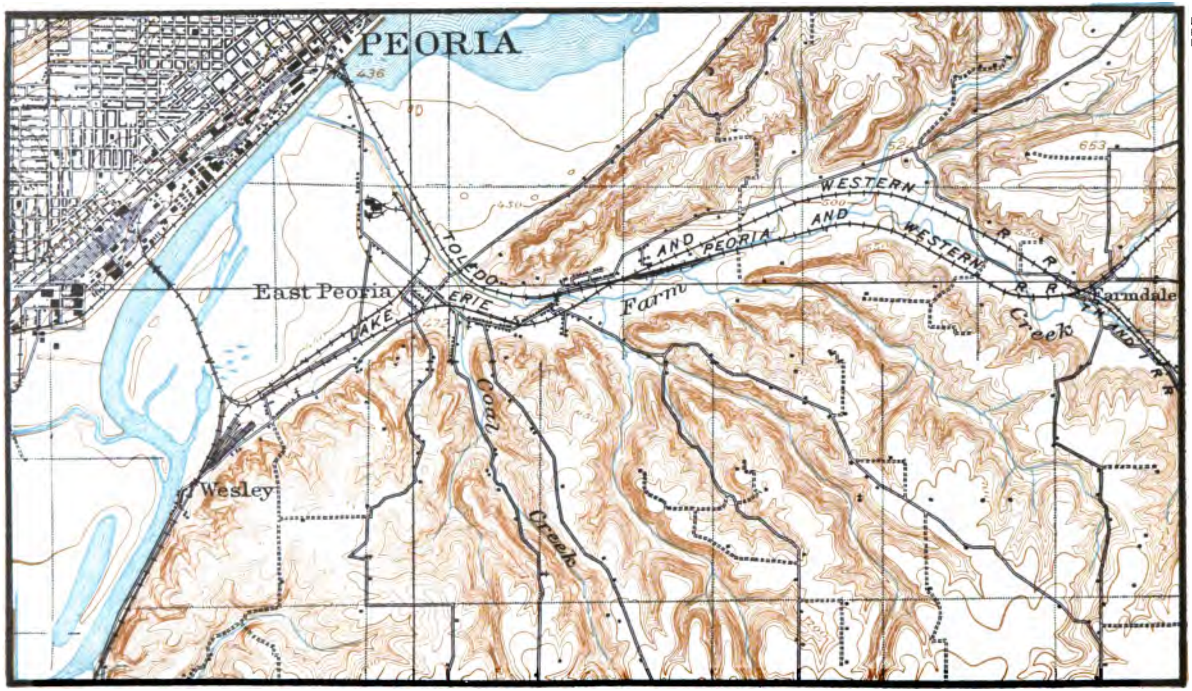


PLATE II. RAVINES AND YOUNG VALLEYS. Contour interval, 10 feet. Scale, about 1 mile per inch. (Peoria, Illinois, Sheet, *U. S. Geological Survey.*)

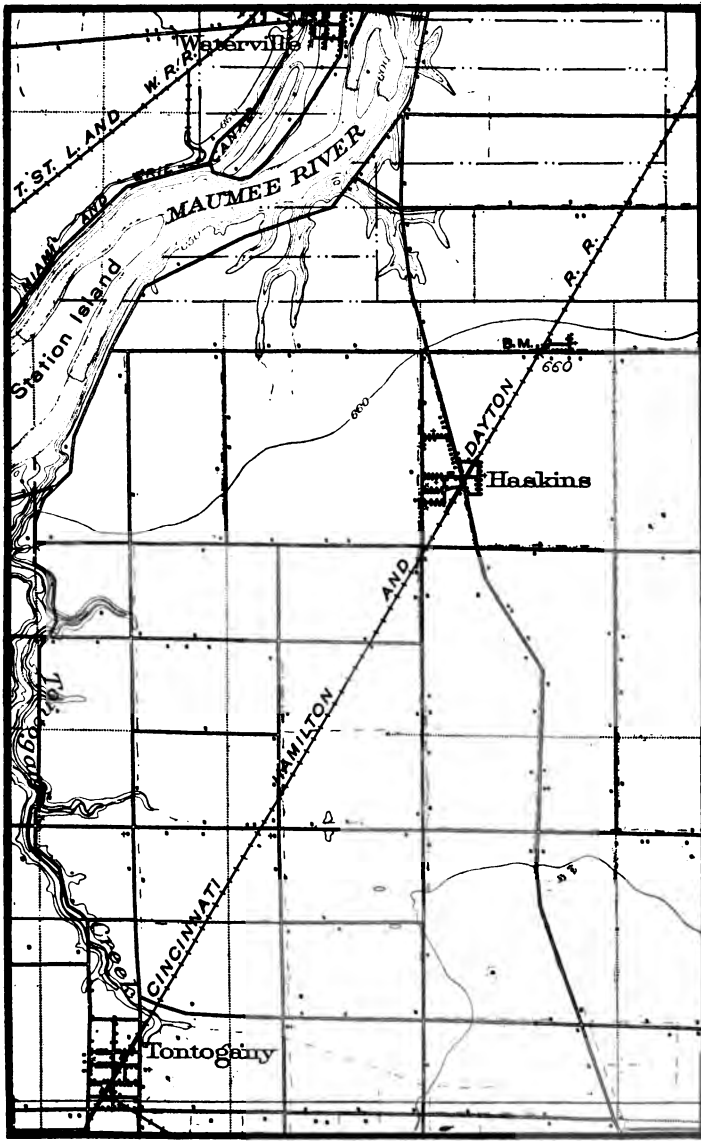


PLATE III. AN AREA IN A YOUTHFUL STAGE OF EROSION. Contour interval, 10 feet. Scale, about 1 mile per inch. (Bowling Green, Ohio, Sheet, *U. S. Geological Survey.*)

early maturity they are roughly U-shaped (Fig. 134), instead of V-shaped, as before. In later maturity they have conspicuous flats. These changes in cross section signify that down

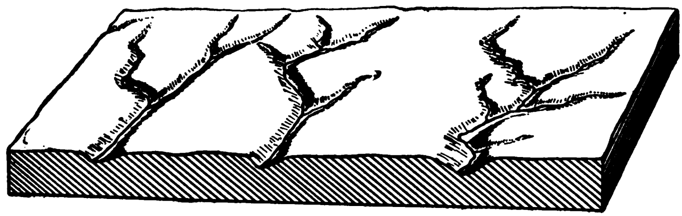


Fig. 137. — Diagram of an area in a youthful stage of erosion. The area is situated some distance from the sea. The bottom of the diagram represents sea level.

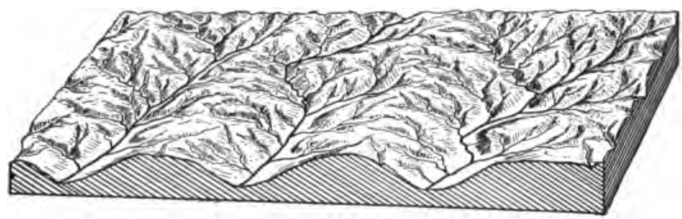


Fig. 138. — Diagram showing mature topography in a region situated some distance from the sea. The bottom of the diagram is sea level. The area shown in Figure 137 will in time closely resemble the present appearance of this area.

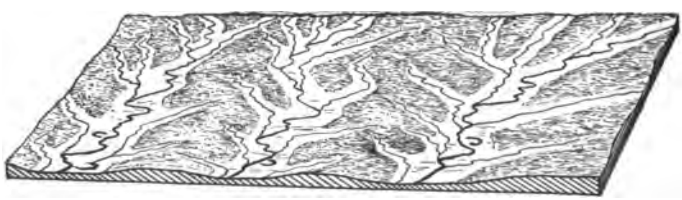


Fig. 139. — Diagram showing old topography in a region situated some distance from the sea. The bottom of the diagram is sea level. Unless diastrophism interferes with the work of the streams, the areas represented in the two preceding figures will finally closely resemble this area.

cutting has come to be very slow, and that the processes which widen valleys and reduce their sides to gentler slopes have become much more important, relatively. Valleys are *old*

when their nearly level, wide bottoms are bounded by low, gently sloping sides (Fig. 135). Figure 136 shows the changing shape of a valley in its advance from youth to old age.

The terms *youth*, *maturity*, and *old age* are applied also to rivers and to the topography of drainage basins. Figures 137, 138, and 139, and Plates III, IV, and V, show young, mature, and old topographies. In Figure 137 the valleys are few in number and have the characteristics described above as distinctive of youth. The region is poorly drained, broad upland areas between the valleys being as yet untouched by erosion. The task of carrying to the sea all the material above base level has scarcely begun. The area shown in Figure 138 has been eroded into a rough hill-and-valley country. Only narrow ridges remain to indicate the position of the once broad inter-valley uplands, while the larger valleys have nearly reached base level. The region, therefore, possesses greatest relief at this stage. Slope is at a maximum, and every part of the area is now reached by drainage lines. When the rivers have reduced a region to old age (Fig. 139), it again approaches flatness at a level as low as running water can bring it. Such a plain, if perfected, would be a *base-level plain.*

It is especially important to note that youth, maturity, and old age are terms which, as used in geology, indicate stages in development and not periods of years. It is perfectly possible, for example, for a large river working on weak material to bring its valley to old age in the same or less time than that required for a smaller stream, opposed by stronger rocks, to develop a mature valley.

Peneplains and monadnocks. — Areas have been rarely, if ever, absolutely base-leveled. The time required is very great, and before the rivers have accomplished the task, the area is likely to have been elevated with reference to sea level and the quickened streams started upon the new task of reducing it again. Extensive areas have, however, been reduced nearly to base level. Such plains are called *pene-*

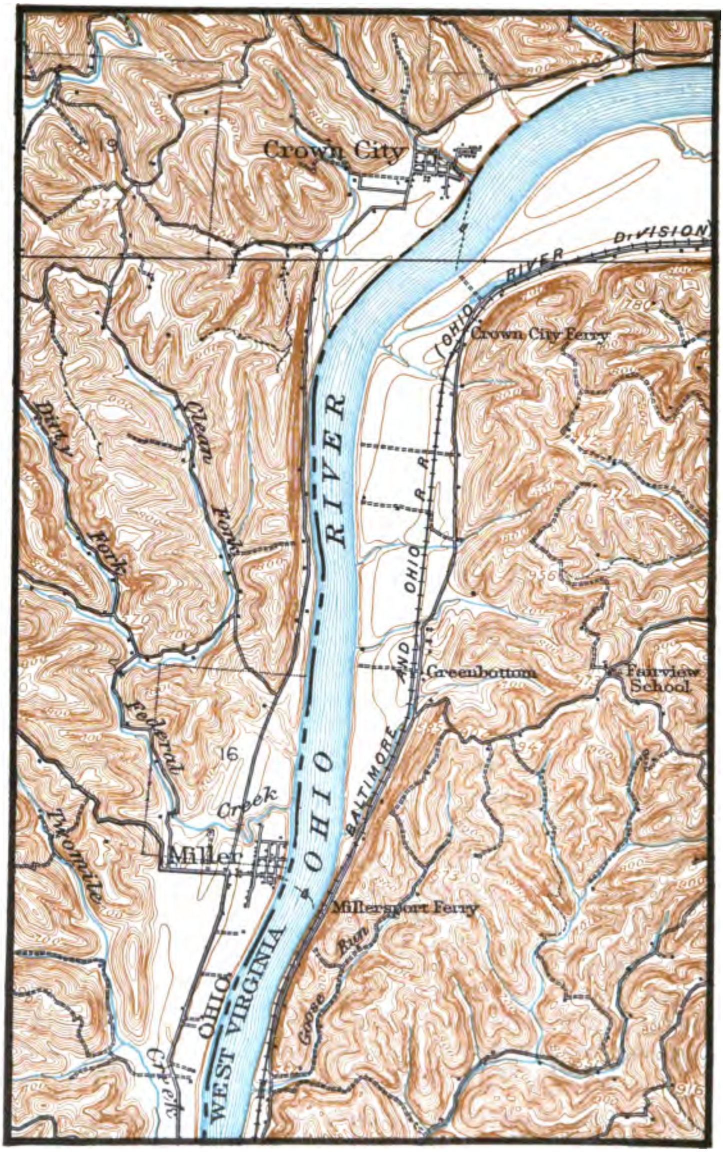


PLATE IV. Mature Topography. Contour interval, 20 feet. Scale, about 1 mile per inch. (Athalia, O.–W.Va., Sheet, *U.S. Geological Survey.*)

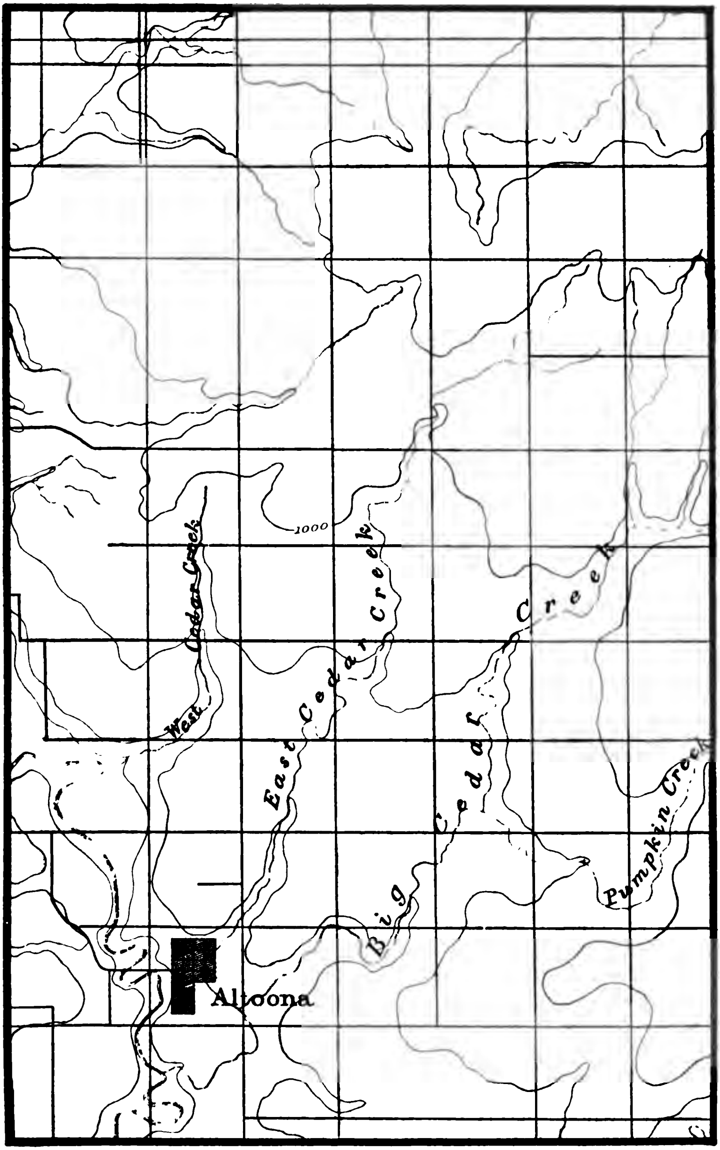


PLATE V. AN AREA IN OLD AGE. Contour interval, 50 feet. Scale, about 2 miles per inch. (Fredonia, Kan., Sheet, *U. S. Geological Survey.*)

plains (almost plains). Above their otherwise flattish surfaces occasional unreduced elevations rise abruptly. These

FIG. 140. — A peneplain near Camp Douglas, Wisconsin, with several monadnocks in the distance. (Sankowsky.)

elevations are called *monadnocks* (Figs. 140 and 141), after a mountain of this type in New Hampshire, and owe their preservation either (1) to the superior resistance of their rocks, or (2) to a favorable position among the streams.

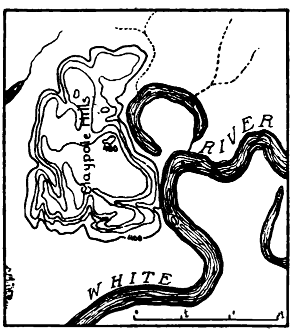


FIG. 141. — A monadnock on the flood plain of a river.

Cycles of erosion. — *A cycle of erosion* is the time required for the production of a base-level plain. From the preceding paragraph it is evident that erosion cycles have been rarely completed. Usually they are interrupted and a new cycle inaugurated.

The erosion history of a region is often recorded by the character of the topography. Thus, meandering courses are developed by rivers only on valley flats, but many a meandering river occupies a valley scarcely wider than the stream itself, and much narrower than the belt within which the river winds (Plate VI). This means that after the development of the meandering course, the region was elevated in such a manner as to increase the gradient,

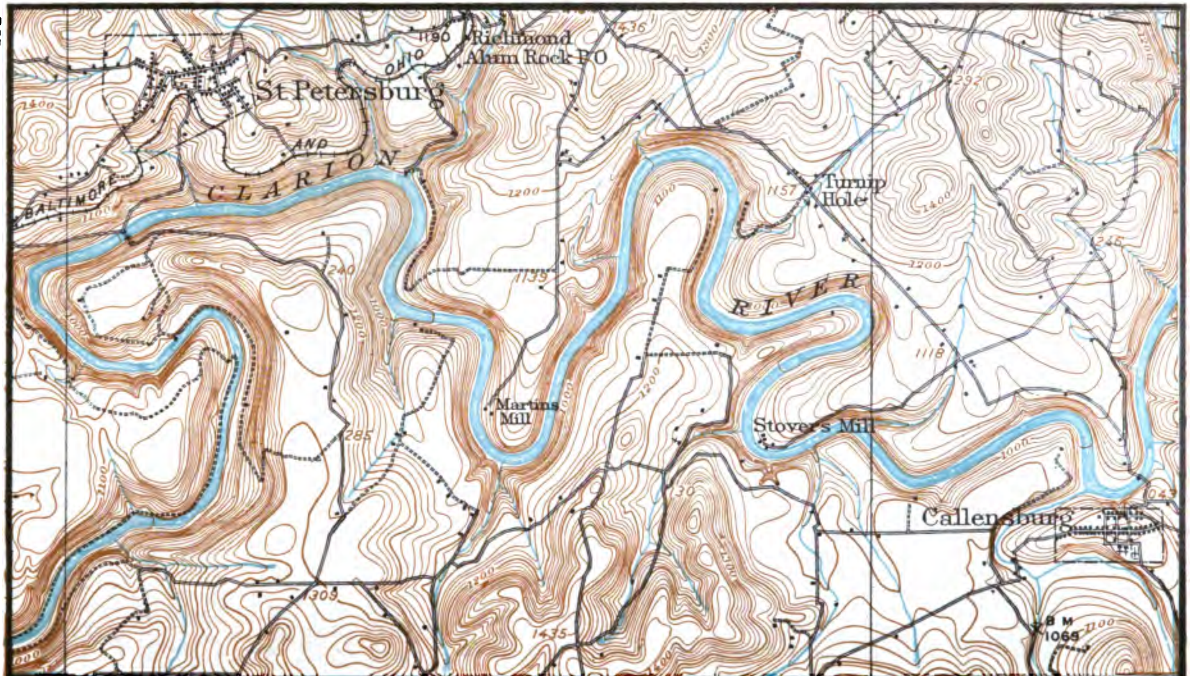


PLATE VI. INTRENCHED MEANDERS. Contour interval, 20 feet. Scale, about 1 mile per inch. (Foxburg, Pennsylvania, Sheet, *U. S. Geological Survey.*)

and so the velocity, of the stream, which was then able to cut a new valley in the floor of the old one. In its growth this young valley followed up the old curves of the river, and these became *intrenched meanders.*

Fig. 142. — Sketch showing recent gorge in older valley. Matanuska Valley, Alaska.

Figure 142 shows a young inner cañon formed in a wide older valley in consequence of uplift. After the river had developed a wide flat, the valley was so elevated as to quicken (*rejuvenate*) the stream, enabling it to cut the new, inner valley. The broad remnants of the old valley flat constitute terraces. River terraces may be defined as benches that

Fig. 143. — Shoshone River at Cody, Wyoming. Shows Shoshone Cañon in the distance, with the south end of Rattlesnake Mountain on the right and Cedar Mountain on the left, also the nearly level surfaces of portions of the successive terraces. Irrigation is carried on extensively on the terraces. (Fisher, *U.S. Geol. Surv.*)

extend along valleys and are above the reach of ordinary flood waters (Fig. 143). Many terraces are not due to uplift (p. 183). A rejuvenated river responds to the elevation first in its lower course, and the new valley formed there extends itself upstream by headward erosion. Until this extension is completed, the upper river, as yet unaffected by the uplift, flows on the relatively broad and gently sloping bottom of the old valley (*A* to *B*, Figs. 144 and 145), while the lower river flows in the narrow, steep-floored new valley (*B* to *C*, Figs. 144 and 145). Such rivers are said to have *interrupted profiles.*

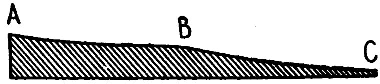


FIG. 144. — Diagram of an interrupted profile.

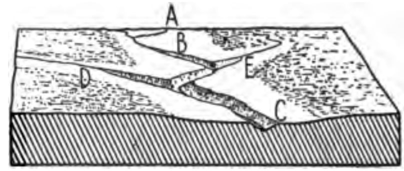


FIG. 145. — Diagram of a rejuvenated area. In what stage of erosion was the region before it was rejuvenated? When did the two lower tributary streams begin to cut new valleys? What are all the things which may have helped to determine the fact that the new valley of the tributary stream "D" is longer than that of "E"? What changes will occur in the character of the topography in the future?

Figure 146 shows in principle the topography and structure of a portion of the Appalachian Mountains. Water-laid beds (What indicates this origin?) were folded into a series of

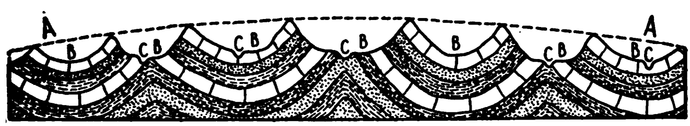


FIG. 146. — Diagram of folded mountains in the youthful stage of the third cycle of erosion. (Modified after Salisbury.)

anticlines and synclines, the former constituting parallel mountain ridges, the latter structural valleys. The area was then worn down to base level, a broad, nearly level plain replacing the mountain topography. The former existence of

this base-level plain is indicated by the fact that the present ridges have even crests and would rise to a common level but for subsequent warping of the region. At any stage preceding extreme old age, the tops of individual ridges would not have been even, and different ridges would have stood at different levels (Why?). Next, the plain was elevated and warped slightly (*A*—*A*), without further folding of the beds, thus beginning the second recorded cycle of erosion. The rejuvenated streams, together with the new tributaries which worked back from them, now opened broad valleys on the weaker rocks at the level *B*—*B*, above which the stronger beds stood as parallel ridges. Finally, the second cycle was

Fig. 147. — The even sky line to the left is the nearly level surface of a peneplain, which bevels across sedimentary and igneous rocks. To the right it cuts tilted Paleozoic beds; to the left pre-Cambrian granite. Since the formation of the peneplain the region has been elevated and eroded. Western Wyoming. (Baker.)

interrupted and the third one begun by the uplift which permitted the streams to cut the new valleys at *C*. The work of reducing the area to base level in the present cycle remains largely to be done. The few new valleys of the larger streams are narrow and steep-sided. The region is accordingly in the youthful stage of the third recorded cycle of erosion.

Figure 147 shows a nearly horizontal sky line, and below it, igneous rocks and tilted sedimentary beds. From what has preceded, it will be understood readily that this nearly level surface was a peneplain, now uplifted and dissected.

Intrenched meanders, interrupted profiles of streams, even-crested mountain ridges, and certain kinds of terraces are accordingly among the features which may indicate more than one cycle of erosion, and which often aid in working out the later geological history of a region.

Questions

1. At what stage in an erosion cycle is the run-off greatest?
2. At what stage in their development are rivers most subject to destructive floods?
3. When in an erosion cycle is the general level of the ground-water surface highest? Lowest?
4. What is (1) the immediate, and (2) the final, effect of stream erosion upon topography?
5. At what stage of an erosion cycle is agriculture most favored?

FIG. 148. — View in the western part of the province of Chi-li, China. The erosion of the gneissic rocks has been aided by recent deforestation. (Willis, *Carnegie Institution.*)

Least favored? At what stage is road building most difficult? (Compare Plates III, IV, and V.)

6. At what stage in the life of a river is it most likely to furnish water power? Navigation?

7. What is the age, in terms of erosion, of the area shown in Figure 148?

8. Make a diagram showing (1) the wet-weather and dry-weather positions of the ground-water surface, and (2) the cross sections of valleys which (*a*) frequently, (*b*) seldom, and (*c*) never, "go dry."

9. Compare and contrast the relief of two topographically mature regions of the same original altitude, one of which is near the sea, and the other far inland.

10. Assuming that the rainfall is equal everywhere and the character of the rocks everywhere the same, what change will occur in the position of the divide now at *a* in Figure 149? When will the divide cease to shift? How will the character of the slopes change after the divide becomes stationary? What would be the effect if the rocks to the left of *a* were harder than those to the right?

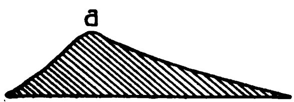


FIG. 149. — Diagram of a shifting divide.

11. What would be the width of valleys if they were due only to the down cutting of streams? What inferences may be made from the fact that most valleys are several times as wide as they are deep?

12. At what stage in its life should a river be engaged chiefly in deepening its valley? In widening it?

13. What is the age, in terms of erosion, of the area shown in profile in Figure 150? The evidence?

FIG. 150. — Profile showing the character of the surface in a portion of southeastern Colorado. Length of section nearly ten miles. Vertical scale about six times the horizontal. (*U.S. Geol. Surv.*)

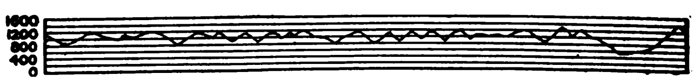


FIG. 151. — Profile of an area in West Virginia, near Charleston. Length of section, 9¼ miles. Figures show elevation above sea level.

14. In what stage of erosion is the region shown in profile in Figure 151? How told? What is the age of the valley at the right end of the section? Of the rest of the valleys?

15. How many cycles of erosion appear to be shown by Figure 152? What is the evidence of each cycle? Is the evidence strengthened

FIG. 152. — Profile across Dunning and Tussey mountains, Pennsylvania. Length of section nearly nine miles. Vertical scale about two and one half times the horizontal. (*U.S. Geol. Surv.*)

by the fact that the beds which underlie the region are tilted? Reasons? In what stage of the present cycle is the region?

FEATURES DUE TO SPECIAL STRUCTURES AND UNEQUAL HARDNESS

Rapids and falls. — A *rapid* is a place in a stream where the current has exceptional velocity (Fig. 153), while a *fall* is a place where the water drops (Figs. 154 and 155). Rapids

FIG. 153. — Chandlar Rapids in Chandlar River, Alaska. (Schrader, *U.S. Geol. Surv.*)

and falls develop in various ways, the more important of which may be noted. If a stream formed by the overflow of a lake (p. 142) were to flow over a vertical cliff, a fall would result. If a main valley were deepened by a glacier,

FIG. 154. — Rainbow Falls of Ausable River, New York. (*U.S. Geol. Surv.*) What kind of rock occurs in the foreground? What appears to determine the position of the little cliff which extends from the lower left-hand corner across the center of the picture?

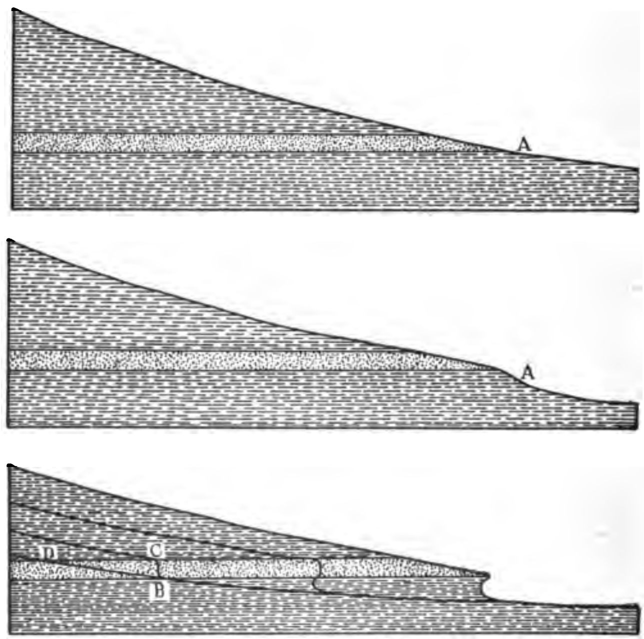
while its tributary valleys were not, and the ice were to disappear subsequently, the bottom of the main valley would be lower than the mouths of the tributaries, whose streams would descend by rapids or falls. Rapids and falls of this origin are common in some of the mountains of western United States (p. 222). Such falls are consequent upon de-

Fig. 155. — Twin Falls of Snake River, Idaho. (*U.S. Geol. Surv.*)

clivities which the rivers had no share in forming, and so have been called *consequent falls.*

A second class of falls is due to escarpments which the streams helped to make; these are called *subsequent falls.* A river flowing on the high gradient shown in Figure 156 is likely to be a degrading river. Obviously, it will wear its channel faster at *A*, where the rocks are soft, than just above, where they are hard. The result is that the gradient, and hence the velocity, of the stream becomes greater at *A* than elsewhere (Fig. 157). In other words, rapids are formed, which become increasingly swift as the gradient becomes

increasingly steep. Finally, a vertical cliff is developed at *A*, over which the stream falls (Fig. 158). The rapids have been replaced by a waterfall. The falling water wears the soft rock faster than the hard rock which overlies it, so that projecting ledges of the hard rock are formed. From time



Figs. 156, 157, 158. — Diagrams to illustrate the development and extinction of a waterfall.

to time pieces fall down from these unsupported ledges, and by this process of undercutting (*sapping*) the waterfall retreats upstream. Downstream from the waterfall the river develops a slope upon which it is at grade. It is evident from Figure 158 that as the waterfall retreats upstream the bottom of the hard fall-making layer approaches the level of the graded channel. Finally, the two meet (at *B*), and the waterfall ceases to retreat because further under-

cutting is impossible. The point of maximum wear is now transferred to the brink of the waterfall at *C*. Wear at this point presently destroys the verticality of the slope, leaving a steep descent down which the water flows instead of fall-

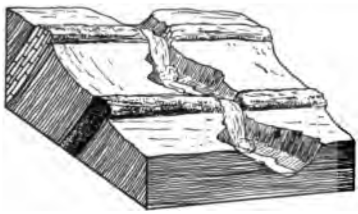


Fig. 159. — Diagram showing falls with beds dipping upstream.

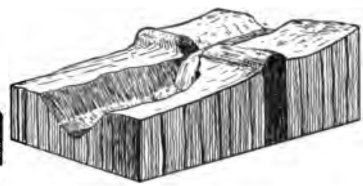


Fig. 160. — Diagram of a waterfall developed on vertical beds.

ing. The waterfall has been succeeded by rapids. Finally, the top of the hard layer is eroded to the level of the graded channel, and the rapids disappear (at *D*, Fig. 158). (What would be the effect of an elevation of the valley?) The same sequence of events would occur if the beds dipped upstream (Fig. 159), but the waterfall would retreat a shorter distance and would, other things equal, be shorter lived. Waterfalls may develop also where the beds are vertical (Fig. 160). (How would the history of such waterfalls differ from the history of those noted before?) Again, waterfalls may develop on beds dipping gently, but not steeply, downstream. (May there be rapids where the beds dip steeply downstream?)

Fig. 161. — Pothole in bed of stream in Smoky Mountains, near Hot Springs, North Carolina. (Trowbridge.)

Where there are eddies in streams, and they are particularly common at the bases of waterfalls and in rapids, stones may be whirled round and round, wearing in the bed cylindrical, well-like depressions, called *potholes* (Fig. 161).

Narrows. — When the rocks in the sides of a valley are of unequal strength, the valley is widened at unequal rates at different points, and if the difference in the character of the rocks is great, the valley may become wide where they are weak, while still narrow where they are strong. The places where valleys have much less than their usual width are called *narrows* or *water gaps* (Figs. 162 and 163). Delaware Water Gap and Harper's Ferry on the Potomac are among the more famous of many narrows in the Appalachian Mountain region. Narrows develop best where there are great differences in the strength of the rocks which form the valley sides, within short distances. They are, therefore, usually associated with highly tilted beds rather than with horizontal ones. They are most conspicuous, also, in connection with mature valleys, for very young valleys are narrow everywhere, and very old valleys have become wide everywhere, regardless of the character of the rocks.

FIG. 162. — Diagram showing water gaps.

FIG. 163. — A typical water gap in the Appalachian Mountains. The Narrows of Wills Mountain at Cumberland, Md. Several roads famous in American history sought the West through this gap. (*Md. Geol. Surv.*)

Cañons. — Valleys that are strikingly deep in relation to their width are called *gorges* (*e.g.* Niagara Gorge), dells (*e.g.* the Dells of the Wisconsin), and especially in the West,

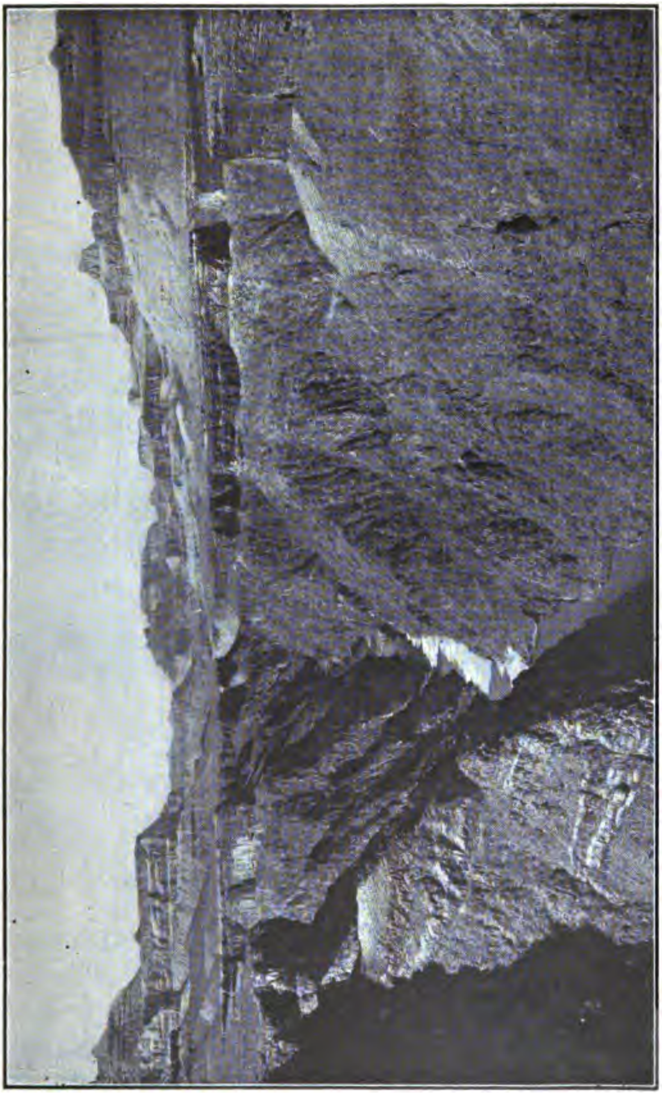


FIG. 164. — Inner gorge of Grand Cañon of the Colorado, Arizona. (Walcott, *U.S. Geol. Surv.*)

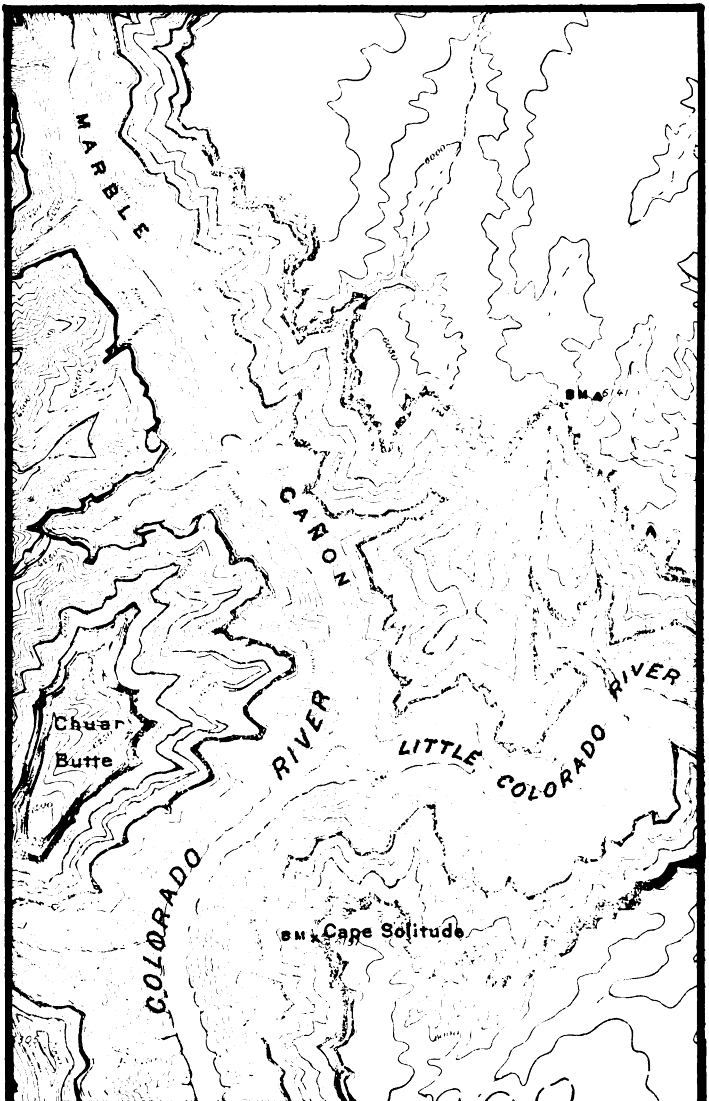


PLATE VII. Portion of the Grand Cañon of the Colorado, and the Mouth of the Cañon of the Little Colorado River. Contour interval, 50 feet. Scale, about ¾ mile per inch. (Vishnu, Arizona, Sheet. *U. S. Geological Survey.*)

cañons. The cañon of the Colorado River (Figs. 164 and 165) is the largest in the world. The Colorado has been able to cut a very deep valley because the surface of the plateau in which it is formed is high above base level. The valley is still narrow because (1) the climate is arid and a number of the agents which widen valleys (p. 140) have accordingly worked slowly, (2) most of the rocks of the

FIG. 165. — Portion of the Grand Cañon of the Colorado River, Arizona. (Walcott, *U.S. Geol. Surv.*)

cañon walls are capable of standing in steep faces, and (3) under these circumstances, the valley has not existed long enough to have been made wide. (How can the river be of large volume when the climate of the region is arid?) Vast as the Colorado Cañon and its tributary cañons are (Plate VII), the region is nevertheless in a youthful stage of erosion, for very little of the work of reducing it to base level has been accomplished. As ages pass, the cañon will be worn slowly deeper and wider by the water and weather, and the side cañons will become larger and more numerous, until finally the great plateau will be reduced to a nearly level plain but little above sea level. (What will be

the topography of the region midway between the present and the final stage?) The conditions which brought about the formation of the Colorado Cañon are those which most favor cañon development. They are (1) a considerable altitude, (2) a dry climate, (3) rocks that will stand in cliffs, and (4) a vigorous stream. As implied above, however, not all cañons and cañon-like valleys are in arid regions. Figure 166 shows a cañon in a moist region.

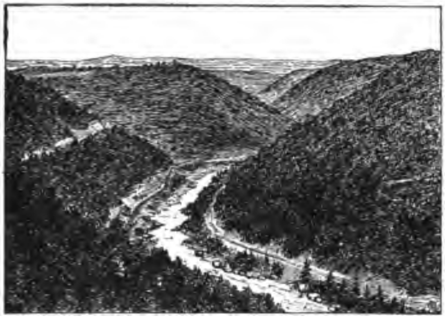


FIG. 166. — A cañon in a humid region. Valley of the New River in the Allegheny Plateau.
What shows that the climate is moist?

Rock terraces. — *Rock terraces* (Fig. 167) occur on the sides of many valleys cut in horizontal beds of unequal strength. The terraces are formed by the strong beds, which are worn back less rapidly than the weak beds above and below them.

Elevations due to unequal erosion. — The relatively rapid erosion of soft rocks has left associated harder rocks standing as conspicuous elevations in many places. If the beds are tilted highly, the resistant ones may be left standing as ridges after the softer ones are worn down to valleys (Plate XVI). This is the origin of the well-defined Appalachian Mountain ridges (p. 153). Smaller ridges, formed in this way on the flanks of mountain ranges, are sometimes called *hogbacks* (Fig. 168). The superior resistance of dike rock may lead to the formation of dike ridges (p. 50). If the beds are horizontal, flat-topped table moun-

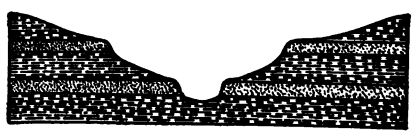


FIG. 167. — Diagram of rock terraces.

tains may develop. In the western part of the United States such an elevation of moderate height and extent is often called a *mesa* (a Spanish word meaning table, pronounced "may-sa"; Figs. 169 and 170). Smaller mesas whose flat tops have been destroyed more or less completely by erosion are frequently called *buttes* (a French word meaning hill, pronounced "bewts"; Fig. 171). The name butte is sometimes applied loosely in the West to any conspicuous hill.

Fig. 168. — A hogback. East flank of Bighorn Mountains, Wyoming. (Trowbridge.)

Rock structure and stream courses.—Joint systems and fissures have in certain places guided the run-off (Fig. 172), producing drainage systems of peculiar and angular pattern. Many streams in the Adirondack Mountains flow along intersecting fault lines. In a region underlain by horizontal beds, lengthening valleys extend themselves in various directions, and the stream courses are without systematic arrangement (Plate IV). In an area of tilted beds of unequal strength, many of the larger streams follow the

Fig. 169. — Mesas. Eastern Arizona. (Fairbanks.)

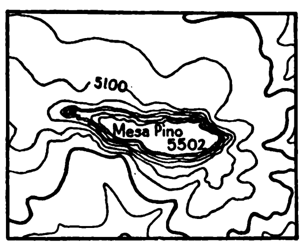


Fig. 170. — Mesa Pino, New Mexico.

outcrops of the weaker layers, while their tributaries join them at right angles, producing a regular drainage pattern (Fig. 173).

FIG. 171. — Pawnee Buttes, Weld Co., Colorado. The dark beds are sandstone; the light ones, shale. (Darton, *U.S. Geol. Surv.*)

In such a region streams are in some cases diverted from courses across hard layers to courses over soft layers. The method by which the change is accomplished may be illustrated from Figures 174, 175, and 176. In Figure 174 the farther stream crosses the resistant ridge-making layers in water gaps, and is unable to cut its valley in the weak rock just above the gaps any faster than it does in the hard rock at the gaps. The nearer stream does not cross the hard beds and, therefore, has cut its valley considerably lower, and is lengthening it rapidly by headward erosion. Presently it will reach and enter the farther valley, and the waters of the latter above the point

FIG. 172. — A valley formed along a joint plane. Enfield Gorge, near Ithaca, N.Y. (Tarr.)

of invasion will become tributary to it, for it will afford them a lower line of descent. In Figure 175 this has occurred. The process by which it was accomplished

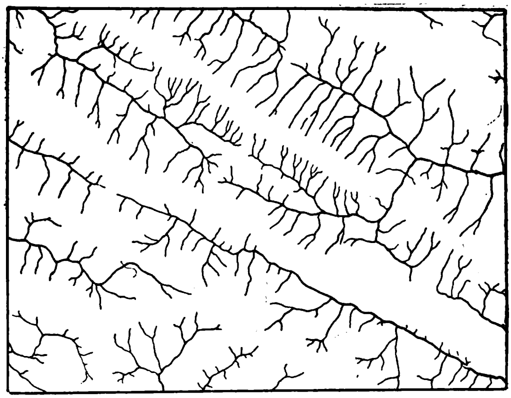
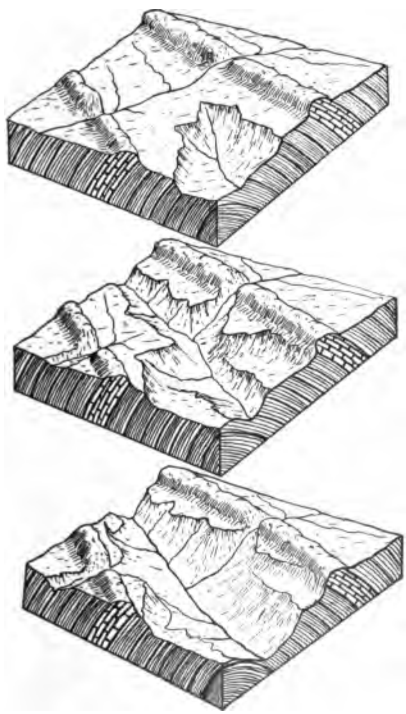


FIG. 173. — Drainage in a region of folded rocks.



FIGS. 174, 175, 176. — Diagrams to illustrate stream piracy.

is known as *stream piracy.* The stream which effected the capture is the *pirate,* while the stream which suffered the loss is called a *beheaded stream.* The drainage captured is said to be *diverted.* The sudden increase in its volume has permitted the pirate (Fig. 175) to cut a new valley in the bottom of its old one, and the remnants of the old valley flat now form terraces. Favored by the lower level afforded by the pirate, the diverted streams have lowered their valleys notably, except above the upper

water gap, whose hard rocks continue to act as a base level for the drainage crossing them. It is evident that the divide between the beheaded stream and the pirate system will shift at the expense of the former, for the slope in that direction is very gentle, while that toward the latter is steep. The result is shown in Figure 176, where the divide has migrated to a permanent position at the outcrop of the hard rock. The beheaded river now rises to the left of the mountain ridge, and the gap, abandoned by the stream which cut it, has become a *wind gap*. Wind gaps are common in the Appalachian Mountains. Through piracy, streams tend so far as possible to get off the hard rocks and upon the soft rocks. Thus they adjust their courses to the structure of the beds. The result is appropriately called *structural adjustment*.

While stream capture is most common in regions of tilted or folded strata, it is not confined to them. A river may be able to capture the waters of neighboring streams because favored by larger volume, less resistant rock, the character or amount of its load, or a shorter course to the sea.

Questions

1. Why are steep slopes characteristic of arid regions?
2. State the conditions necessary for the development of a subsequent falls.
3. Enumerate all the factors upon which the length of life of a given waterfall will depend.
4. What inference concerning the structure of the beds underlying a given region may be made: (1) From the fact that its elevations are ridges in parallel arrangement? (2) From the fact that the eastern slopes of its north-south ridges are relatively long and gentle, while the west-facing slopes are short and steep? (3) From the fact that its elevations are without systematic arrangement?
5. How many cycles of erosion are recorded by Figure 162?
6. (1) What is the age of the valley shown in Figure 177, and how is it shown? (2) What kinds of work is the river doing? (3) How will the river modify its valley in the future? (4) What was the origin of the waterfall? (5) What will be its future? (6) What

evidence is there of weathering? (7) What are probably the chief agents of weathering here? (8) Is there evidence of diastrophism? If so, what?

FIG. 177. — South Fork of Birch Creek, a tributary of the Yukon River, Alaska. (Prindle, *U.S. Geol. Surv.*)

STREAM DEPOSITS

Causes of deposition. — (1) Anything which checks the velocity of a loaded stream occasions the deposition of sediment. (*a*) A decreasing gradient is an important cause, especially in the middle and lower portions of large valleys. (*b*) Rivers which flow through regions of scant rainfall frequently lose water both by rapid evaporation and by sinking into the ground (Fig. 178). (Where in the United States is this

FIG. 178. — Tejunga River, southern California, sinking in the sand of its flood-plain. (Fairbanks.)

the case over large areas?) Diminished volume means reduced velocity and carrying power, and hence deposition. (c) Many rivers deposit at their mouths where the current is checked. (d) Deposition is brought about also by changes in the shapes of river channels. If, for example, water charged with sediment leaves a narrow, straight, and smooth section of the channel to enter a wide, crooked, and irregular one, the friction of the current with the bed and banks is increased, its velocity is therefore decreased, and deposition may result. (2) Tributaries with high gradients often deliver to their sluggish main streams more sediment than the latter can wash forward, resulting in deposits along the floor of the main valley. In many large depositing

FIG. 179. — An alluvial fan in the Illinois Valley. The velocity of temporary, wet-weather streams is reduced as they leave the gulley in the background, and they are forced to deposit the sediment which they carry. (*Ill. Geol. Surv.*)

FIG. 180. — Alluvial fan at mouth of Aztec Gulch, Dolores Valley, southwestern Colorado. (*U.S. Geol. Surv.*)
Account for the small fan in front of the large one.

rivers, like the lower Mississippi, all the above causes, and perhaps other less important ones, are in operation.

The principal features produced by stream deposition are described in the following paragraphs.

Fans and cones. — *Alluvial fans* are so called because they are half-circular in ground plan when developed typically, and are composed of alluvial material (Figs. 179 and 180). *Cones* are relatively steep fans. Alluvial fans vary in diameter from a few feet to several miles. Some of the California rivers have built fans some forty miles across. Fans are developed best at the bases of steep slopes in dry regions, where streams of diminishing volume leave the relatively high gradients of their mountain valleys to enter lowlands. The deposit in such a situation chokes the channel of the stream, and some of the water spreads around the obstruction. The process being repeated many times, and the stream meanwhile extending the deposits in the direction of its flow, they presently acquire more or less of the "fan" shape which suggested their name. The main water channels of many large fans give off branches that in turn divide repeatedly downstream. These branching channels are called *distributaries*, and their explanation is involved in what has already been said. The deposits in a given channel reduce its size until some of the water breaks over the side and follows a new course to the margin of the fan. The new channel, becoming choked, gives off other distributaries, which divide again. The spreading of the water flowing over the fan becomes an important cause of deposition, since it increases the friction of flow, and therefore decreases the velocity. Deposition may be caused also by much or all of the water sinking into the porous material of the fan. Thus the growth of fans is due to deposition brought about by (1) decrease in gradient, (2) increase in friction of flow, and (3) often by decrease in volume. Plate VIII shows a portion of a large fan, together with waste channels, tributaries, and distributaries.

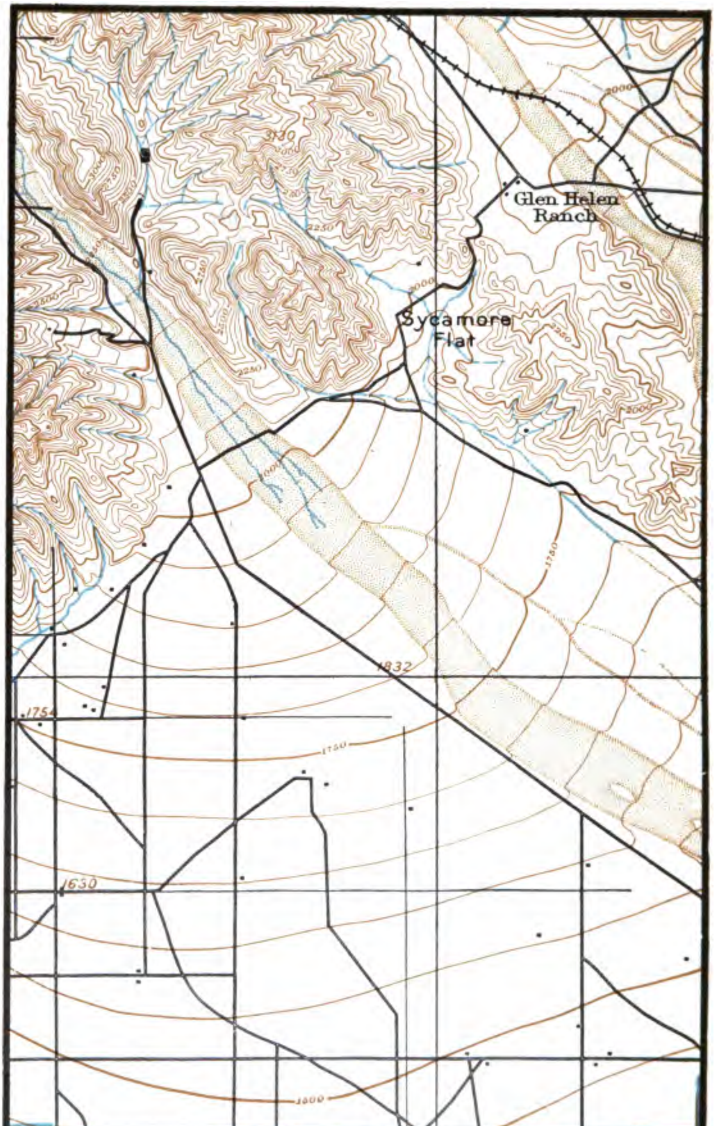


PLATE VIII. PORTION OF A LARGE ALLUVIAL FAN IN SOUTHERN CALIFORNIA. Contour interval, 50 feet. Scale, about 1 mile per inch. (San Bernardino, California, Sheet, *U. S. Geological Survey.*)

The structure of alluvial fans is characteristic, and results from the method of their growth. The coarsest material is dropped at the apex of the fan, where the current is first checked, and the deposit made at any given time becomes progressively finer toward the margin. This does not mean that the material in a vertical section through an alluvial fan, all parts of which are at the same distance from the

FIG. 181. — Section of an alluvial fan, Owens Valley, Cal. (Trowbridge.)

apex, is all of the same degree of coarseness. On the contrary, the material would probably change frequently, both horizontally and vertically, for the volume (and so the carrying power) of different distributaries would vary at the same time, and that of any given distributary at different times. Such variations in the tops of fans may often be seen in the sides of the channels which trench them (Fig. 181).

The angle of slope of a fan depends upon how suddenly and how much the velocity of the depositing waters was diminished, and upon the kind and amount of material they carried. A sudden and great reduction in the velocity of a stream heavily loaded with coarse material, gives a relatively steep slope; the opposite combination a gentle one. The profile of a fan along any radius, like the profiles of other depositional slopes, is a curve concave upwards

(Fig. 182). (What would be the character of a curve drawn on the surface of a fan along a line all points in which were equidistant from the apex of the fan?)

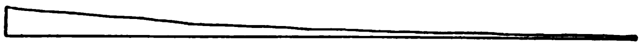


FIG. 182. — Profile of a large alluvial fan near Cucamonga, Cal. Length of section, 6½ miles.

The growing fans of neighboring streams in arid regions unite in many cases to form extensive alluvial slopes or plains (Fig. 183).

Certain rivers have been ponded back by the fans of tributaries, forming broad, lakelike expansions of the river.

FIG. 183. — A piedmont alluvial plain, Silver Peak Range, Nevada. Waste from the mountain valleys unites to form a compound fan. (Sketch from photograph by Spurr, *U.S. Geol. Surv.*)

Lake Pepin in the upper Mississippi, and Lake Peoria in the Illinois River (Plate II), are of this origin.

Flood plains. — The portion of a valley bottom subject to inundation is called the *flood plain* (Plate IX). Flood plains, or flats, are usually formed primarily by the side cutting of relatively sluggish streams (p. 140), and subordinately by deposits made during overflow. In exceptional cases rivers occupying narrow-bottomed valleys are forced to aggrade their channels, and flood plains result that are due entirely to deposition (Fig. 184). The alluvial deposit may cover the underlying rocks thinly or thickly.

Normal flood plains are widest in their lower portion, where the gentle gradient favorable to lateral shifting was developed first, and become narrower more or less regularly up valley. The lower Mississippi has opened a flood plain from 20 to 60 miles or more wide. The downstream slope of flood plains varies with the volume of the stream and the character of the material it deposits. Relatively small streams heavily overloaded with coarse material build steep flood plains, sometimes with a descent of 50 to 75 feet a mile; large rivers, depositing fine sediment, build nearly level flats.

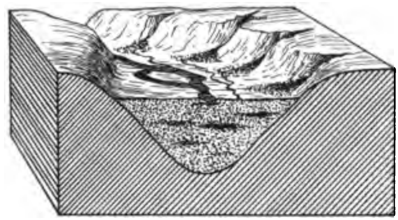


FIG. 184. — Diagram of a flood plain formed by deposition in a narrow valley.

What is the age of the rock valley in which the filling has occurred, and how is it shown? What work was the river doing before filling commenced? The evidence? What things may have forced the river to cease its earlier work and aggrade its valley?

Natural levees. — During times of flood a river deposits most actively along the edges of the channel. Here the depth of the overflowing water is diminished suddenly and, in consequence, its velocity and carrying power. Here during the continuance of the overflow the marginal waters of the main current are checked by friction with the slower moving backwaters. Deposition along these lines during many overflows may build low, marginal ridges with a gentle slope away from the river. Such embankments are *natural levees* (Fig. 185). It is evident that natural levees will not prevent subsequent overflow, since a stream can build them only to the level of its

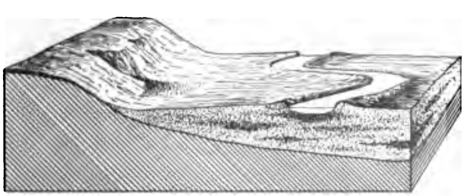


FIG. 185. — Diagram showing natural levees and the general structure of stream-laid beds.

flood waters. Artificial embankments have been built upon the natural levees of many rivers, in order to reclaim their bottom lands. As deposition continues along the bed of the river, such embankments must be built higher from time to time in order to confine the stream.

The low margins of many wide flood plains are marshy. In such marshes, the dead leaves, twigs, and branches of the swamp vegetation gather in the shallow water, along

FIG. 186. — Meanders of the upper Green River, Wyoming. (Baker.)

with minor quantities of silt. This vegetal matter, preserved by the water from complete decay, may be transformed slowly into peat. Some coal beds are thought to represent similar marshes which existed ages ago (pp. 378, 380).

Many tributary streams on entering an aggraded valley are prevented by the natural levees from uniting with the main river at once, and flow greater or lesser distances down valley before joining it at some point where it swings to their side of the flood plain (Plate IX).

Braided rivers. — In some cases the waters of rapidly depositing rivers flow in numerous channels which meet and divide repeatedly. Deposition along the floor of a given channel reduces its capacity. When the channel is presently unable to hold all of its water, a part breaks over the side and follows a new line. The new channel, becoming choked like the old one, gives off branches which in turn divide. The overflowing waters follow the lowest accessible lines of

descent, and may reunite only to separate again a little farther down valley. By this process the river is split into many minor streams which shift continually and inclose changing islands of sand and gravel. Such rivers are *braided rivers.*

Stream meanders and flood-plain lakes. — Even if nearly straight in the beginning, a river must come to follow a

FIG. 187. — Meanders of the Jhelum River in the valley of Kashmir, India.

serpentine (*meandering*) course (Figs. 186 and 187) on a flood plain of low slope. This results primarily from the fact that its sluggish current is turned against the banks easily by irregularities of the channel, by the currents of tributary streams, and in other ways. The current cuts into the banks where it strikes them. As it issues from a cut in the bank, it is directed against the opposite bank a little farther downstream, and forms a curve there. The development of this bend leads to the formation of another, and so on. As erosion continues, the cuts tend to become smooth curves, better adapted to the regular movement of the current. At the same time the stream erodes these curves, where the current is relatively swift, it builds up to flood level the opposite side of the channel, where the water is slack. In this way it comes to follow a more or less regularly curved course suited to its volume and gradient. As

the process of cut-and-fill continues, the curves change in outline as suggested by Figure 188. Finally the stream cuts through the narrowing neck of land between the two limbs of a meander (Fig. 189). The current now abandons the old roundabout course because the new route is steeper. The old channel is isolated presently by the shifting of the stream to another position on its flood plain, or by deposition at the ends of the abandoned meander, whose standing waters check the edge of the current. The resulting lake is an *ox-bow lake.* The flood plain of a great river, such as the Mississippi or Missouri (Plate IX), may contain numerous lakes, which record recent changes in the position of the river (Fig. 141). The extent to which certain great rivers are shifting their channels is shown by surveys of their courses. Figure 190 shows the changes that occurred in the position of a portion of the Missouri River between 1852 and 1879, and between the latter date and 1894. It shows also the tendency of the meanders to work down the valley.

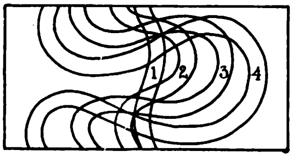


FIG. 188. — Diagram showing development of a meander. The current directed against the downstream side of the meander is on the average stronger than that directed against the upstream side, and therefore the growing meander migrates down the valley.

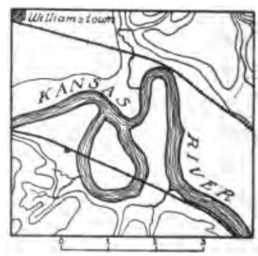


FIG. 189. — A recently developed cut-off. What shows that it is of recent origin?

Ox-bow lakes, like lakes of other origin, are temporary features. They are filled gradually (1) by the encroachment of marsh vegetation upon their shallow borders, (2) by silts deposited in them during exceptional floods, (3) by wind-blown material, and (4) by wash from the surrounding land. Doubtless many generations of lakes are made and destroyed during the formation of great flood plains.

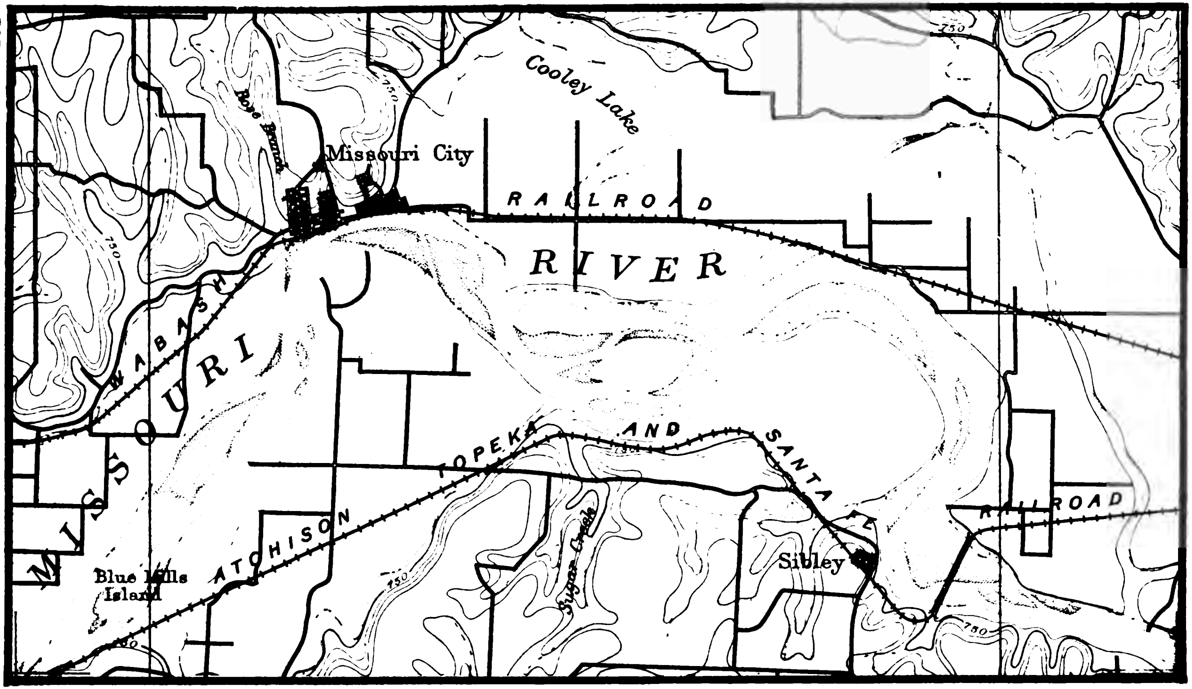


PLATE IX. A PORTION OF THE FLOOD PLAIN OF THE MISSOURI RIVER. Contour interval, 50 feet. Scale, about 2 miles per inch. (Independence, Missouri, Sheet, *U. S. Geological Survey.*)

The materials and structures of flood plains. — As already implied, the materials of flood plains range from coarse gravel to finest mud. The coarser material deposited by a river is confined in general to the vicinity of the channel, where the velocity of the overflow is checked first and most. This grades more or less irregularly into the fine muds which gather in the quiet backwaters. When the river changes its position on its valley floor, the coarser deposits along the new channel cover finer deposits made at a distance from the old channel, whose coarser material is in turn buried with fine. Frequent changes in the position of the aggrading river result in many vertical alternations in coarseness among its sediments. Minor variations may be brought about by the unequal strength of the overflow, capable of moving particles of varying size to a given place at different times. Further complexity in the distribution of the materials of a flood plain is introduced by irregular contributions made by wash from the bluffs and by tributary streams. Figure 185 shows the general structure of stream-laid beds.

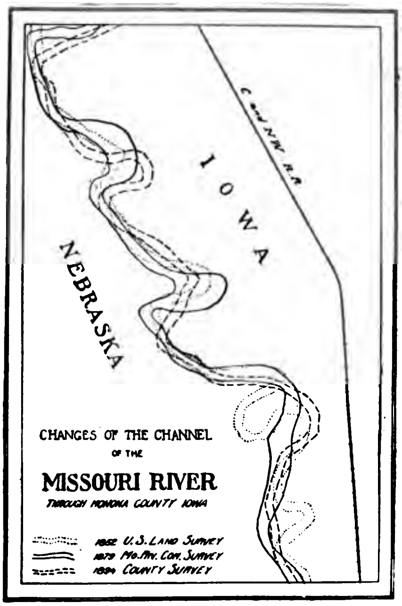


FIG. 190. — Map showing changes in the course of a portion of the Missouri River.

The structure described above has made it possible to determine that certain ancient formations were laid down on the land by rivers, and not in lakes or the sea.

Alluvial terraces. — Under new conditions, a river which has been depositing may find itself underloaded. The change may be due to a movement of its valley resulting in a steeper gradient, to an increase of volume, to a decrease in the amount of sediment received from its headwaters, or to still other causes. Whatever the cause, the river, if greatly underloaded, sinks its channel rapidly. The remnants of the old flat then stand as *alluvial terraces* on one or both sides of the valley (Fig. 191). After the river has opened out a new flood plain at a lower level, for some reason it may again degrade actively, leaving a second set of terraces. Indeed, this process may be repeated a number of times. If a river which has been aggrading is able, under changed conditions, to degrade, but remains nearly loaded, it may shift from side to side of its valley while it slowly lowers its channel, and by this means form a series of terraces. This is illustrated in Figure 192, where a stream is supposed to have filled its valley to the level *A–D–B*, and to occupy a position near the left edge of its flood plain, at *A*. If the stream now shifts toward the opposite side of the valley, meanwhile degrading, it will occupy presently the position *C*. Should movement to the right stop there, because of contact with a projection of the valley wall, or for some other reason, and the river return toward the left side of the valley, a remnant of the old flood plain, *C–D–B*, would remain as a terrace. In similar manner, should the river fail to reach the left side of its valley on the re-

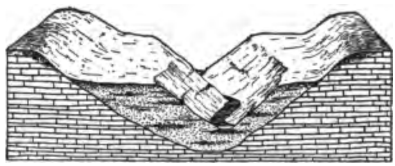


Fig. 191. — Diagram of high alluvial terraces.

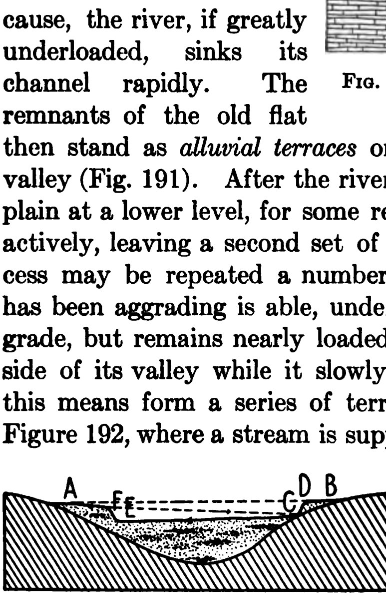


Fig. 192. — Diagram to illustrate the formation of terraces by a river which is degrading slowly, and shifting from side to side of its valley at the same time.

turn swing, a terrace would result, as at E–F–A. Many terraces at successively lower levels might result from a continuation of this process. These terraces might extend a considerable distance along the valley, or only a short distance, and their width might vary notably. It is evident that when formed in this way, terraces upon opposite sides of a valley will not correspond in elevation. Small terraces are common even in young valleys, where they are due in many cases to the fact that, as the streams degraded, they also shifted their positions laterally.

FIG. 193. — Delta of the Mississippi River.

Terraces may be destroyed wholly or in part by the widening of the flood plain at a lower level. Indeed, since the goal of stream-borne waste is the sea, the depositional features discussed in the preceding paragraphs may all be regarded as composed of material which has been dropped only temporarily by overloaded streams, and which sooner or later will resume its journey to the ocean.

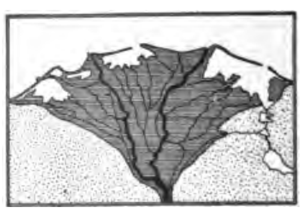


FIG. 194. — Delta of the Nile River. The dotted area is desert.

Many cities are located partly or wholly upon the terraces of great rivers. Peoria, Illinois

(Plate II); Dubuque, Iowa; and Hartford, Connecticut, are examples. Miller and Crown City (Plate IV) are examples of hundreds of villages situated similarly.

Deltas. — Some of the material which rivers bring to the sea or to lakes is carried away by waves and currents; much of it often accumulates off the mouths of the rivers, especially if they flow into tideless or nearly tideless bodies of water.

Fig. 195. — The delta of the Alsek River, Alaska. Shows numerous distributaries. (Netland, *U.S. Boundary Commission.*)

Such deposits may form *deltas* (Fig. 93). Deltas are so called from the Greek letter (Δ) of that name, whose shape they occasionally resemble (Fig. 194).

As the current is checked at the mouth of a river flowing into the sea, the coarsest of the sediment is dropped first, forming slanting beds, whose angle of slope is determined largely by the size and shape of the material. The finer sediment settles less rapidly, and is spread by waves and tides over a larger area in nearly horizontal sheets. As deposition continues, the steeper beds of coarser material are built out upon the nearly level beds of fine. When this submarine embankment is built up close to the surface of the water, it becomes in effect an extension of the river bed, across which the projected current rolls and drags material, and upon which it deposits a part of its load. Deposition on the submarine platform is most active along the edges of the river current, because of friction with the relatively

quiet sea water. Thus levees develop, and the delta is built above the level of the sea. As the original channels across the delta gradually fill with sediment, some of the water breaks over the sides, following new courses to the sea and building up the different parts of the delta in turn. By this means a complicated system of distributaries may be formed (Fig. 195). Portions of the shallow sea covering the submarine platform are sometimes inclosed by the river deposits or between them and the old shore line, forming delta lakes. This was the origin of Lakes Borgne and Pontchartrain, on the delta of the Mississippi near New Orleans (Fig. 193). Extensive deposits of peat may accumulate in delta lakes and swamps. Apart from the shallow basins of their lakes and marshes, and the low ridges along their distributaries, the land surfaces of great deltas are nearly level, continuing the slope of the flood plain farther up river. The upper beds of a delta, deposited by the river upon the submarine flat, are nearly horizontal. Deltas are accordingly characterized by three sets of beds (Fig. 196). The bottom and top beds are nearly horizontal, while the middle beds are inclined more or less steeply.

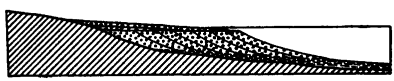


FIG. 196. — Profile and section of a delta.

Deltas grow at very unequal rates. The ratio between the volume of sediment brought by the river and the strength of waves and currents off the river mouth is a chief determinant. The Mississippi brings down about 7,500,000,000 cubic feet of sediment a year; and as the tides of the Gulf of Mexico are weak, the delta is being extended seaward off the mouths of the main distributaries at the rate of about a mile in sixteen years. It appears to have grown at about this rate for many years. An English writer reported in 1770 that the Balize, a small fort built by the French on a little island which was at the mouth of the river in 1734, was then two miles up. The depth of the water into which a delta is being built also in-

fluences the rate of its forward growth. Furthermore, great deltas are as a rule sinking slowly, and the relation of up-building to subsidence varies greatly. In some cases, for example the Mississippi and Ganges, rivers have built up their deltas faster than the region has subsided. In other cases, subsidence is so rapid as to prevent the building of deltas above the sea. In the Chesapeake Bay region recent subsidence has formed great estuaries, and the rivers are now building marshy bay-head deltas. The delta of the Mississippi has an area of over 12,000 square miles, and the compound delta of the Ganges and Brahmaputra rivers is between 50,000 and 60,000 square miles in extent (about as large as the state of Illinois). As a result of long-continued subsidence and up-building, delta deposits may attain great thickness.

Ancient delta beds of great thickness, their origin revealed by their structure, occur in certain localities, — for example, in the vicinity of Puget Sound. They afford a record of the physical geography of the region at the time when the sediments, later changed into firm rocks, were deposited.

Questions

1. How could one distinguish in the field between an ancient alluvial fan and an ancient delta?

2. (1) What occasioned the building of the fan shown in Figure 197? (2) Is the front of the fan the same as when built? (3) If not, how has it been changed, and by what? (4) Account for the trench which crosses the fan. (5) How may the miniature terraces within the trench be explained?

3. What are the general conditions which occasion the development of distributaries?

4. What are all the ways in which Plate IX shows that the Missouri River is there a depositing stream?

FIG. 197. — A small fan on the beach of Lake Michigan.

5. Compare the downstream slope of the higher and lower terraces of a given valley.

6. Interpret Figure 198, indicating (1) the successive steps in the development of the features shown, and (2) how the several changes

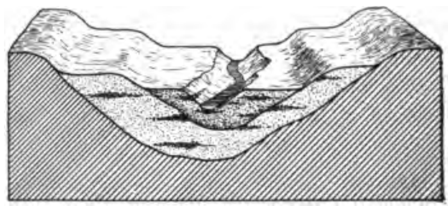


FIG. 198. — Diagram of stream terraces.

that are recorded in the work of the river may have been brought about.

7. Why are the materials brought by great rivers to the sea usually fine (though unequally so)?

8. Interpret the fact that limestones containing marine fossils are sometimes found interbedded with delta deposits.

SUMMARY

The mission of running water is to wear the land to base level. The material it carries toward and to the sea is prepared for transportation largely by the agents of weathering, and in subordinate amount is worn from the rocks by the streams themselves. The irregular reduction of the land produces most of the familiar relief features of the surface, whose characteristics are determined by several factors, especially by the character and structure of the rocks from which they were carved, and the stage of development which they have reached. The waste of the land is often laid aside on its way to the sea by overloaded streams, forming topographic features subject to later destruction by eroding waters or by other agencies.

The getting of the land into the sea has been the great task of streams throughout all the geological ages since lands and seas existed, and the materials of the sedimentary rocks of existing lands represent for the most part the stream-borne

waste of ancient lands, brought to shallow seas which occupied the areas where the rocks occur. Ancient peneplains and other phenomena show that at various times in different places the streams of past ages have nearly completed their task, only to have it renewed when their basins were rejuvenated by a sinking of the sea or by an uplift of the land.

It is evident from the preceding pages that the activities of streams are of prime importance in shaping the present chapter in the history of the earth. It will be seen in subsequent pages that the results of stream activity, with which the student is now familiar, are likewise of prime importance in deciphering the earlier chapters of the earth's history.

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CHAPTER VI

GLACIERS

Characteristics of Glaciers

Formation of snow fields and ice fields. — When the water vapor of the air condenses at temperatures below the freezing point, it is usually as ice crystals, which form snowflakes. Above an irregular surface in the air all points in which have a temperature of 32° Fahrenheit (the isothermal surface of 32°), condensing water vapor accordingly usually forms crystals of ice, many of which become snowflakes, while below it the moisture condenses as water, and forms cloud particles or raindrops. This surface of 32° Fahrenheit is encountered at varying altitudes. It is high near the equator (15,000 to 18,000 feet above sea level), and is at sea level in certain polar regions. In many places, as in northern United States, for example, its position varies notably with the seasons; it is higher in summer and lower in winter. In sufficiently high places in low latitudes and over wide areas in high latitudes, it is at or near the surface during much or all of the year. In such situations more snow falls in the colder months than is melted and evaporated in the warmer ones. The line above which snow is always present is called the *snow line*. While the position of the snow line is influenced chiefly (1) by temperature, it varies also with (2) the amount of snowfall, being lower when the snowfall is heavy and higher when it is light, and (3) the character of the topography, for some situations favor the gathering of snow and afford protection against the sun, while others do not. In general it does not depart greatly from the summer position of the isothermal surface of 32°.

Fig. 199. — Snow fields in the Alps Mountains. Looking from the summit (15,215 feet above sea level) of Monte Rosa, Switzerland, into Italy. (R. T. Chamberlin.)

Long-lived accumulations of snow constitute *snow fields* (Figs. 199 and 200).

Snow fields become *ice fields* by the same processes which transform many snow banks into ice banks each winter. The bottom snow is compressed by the weight of that above and becomes more and more compact, the result being much as when snow is packed into an icelike mass in making snow-

FIG. 200. — Snow fields of Monte Rosa, Switzerland. (R. T. Chamberlin.)

balls. Water from rains and from surface melting during the warmer periods sinks into the snow beneath, and when it freezes helps to cement the mass. Still other processes aid in the change, and the originally loose snow passes by degrees into compact ice.

Formation of glaciers. — When the ice has formed in sufficient quantity, it begins to spread from the place of origin. If formed on plains or plateaus, ice fields are thickest at or near their centers, thinning more or less regularly to the margins, where wastage balances snowfall. In such situations the ice accordingly moves slowly under its own weight in all directions from the center. If formed in and about the heads of mountain valleys, snow fields and ice fields acquire a slow movement down valley. When ice fields start to move, they become *glaciers*.

FIG. 201. — Temporary snow banks, snow fields, and valley glaciers of various sizes. Alaska. (Netland.)

A glacier spreading in all directions from its center on a plain or plateau is an *ice sheet* or *ice cap* (Fig. 212). Glaciers confined to valleys are *valley glaciers* (Figs. 201, 202, and 203, and Plate X). Compound glaciers formed on plains or plateaus at the base of mountains by the union of valley glaciers which have spread out in front of the mouths of their mountain valleys, are *piedmont* (foot of the mountain) *glaciers* (Fig. 211).

VALLEY GLACIERS

Distribution and size.— There are hundreds of valley glaciers among the mountains of Alaska, western Canada, and northwestern United States. Here high mountains near the coast force the vapor-laden ocean winds to precipitate much moisture in the form of snow. Seward Glacier, the largest valley glacier in Alaska, is over 50 miles long and 5 miles and more wide. Very few glaciers in the United States are more than a mile long. There are nearly two thousand glaciers in the Alps Mountains. The longest of

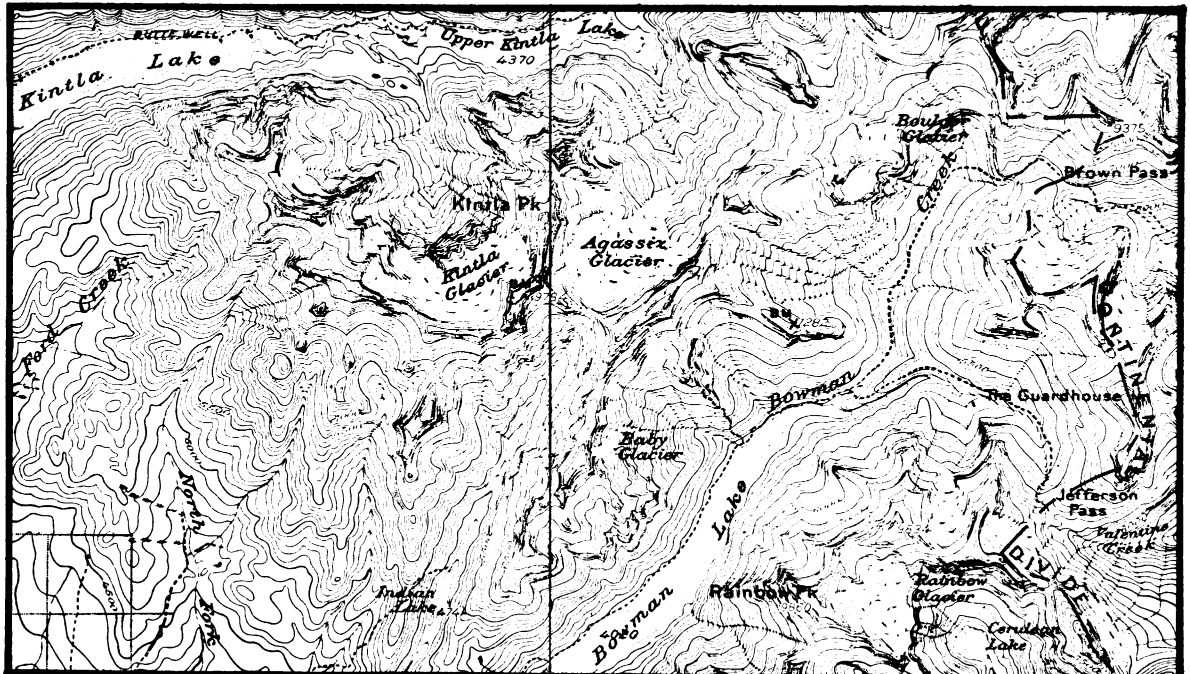

PLATE X. GLACIERS IN MONTANA. Contour interval, 100 feet. Scale, about 2 miles per inch. (Kintla Lakes, Montana, Sheet, *U. S. Geological Survey.*)

them measures over 10 miles, but the great majority are less than a mile in length. They vary in width from a few hundred feet in the case of the great majority, to a mile or more. The

FIG. 202. — Glacier de la Brenva descending from Mont Blanc on the Italian side. (R. T. Chamberlin.)

largest ones are several hundred feet thick. Large valley glaciers occur also in the Caucasus, Himalaya, and other mountains.

Feeding grounds. — Deep snow fields occupy the heads of mountain valleys containing glaciers. Fed by snowfall in the valley, by avalanches from the inclosing slopes, and by wind-

swept snow from the surrounding crags and peaks, the snow fields constitute feeding grounds for the glaciers which descend from them. The larger part of the snow of such fields is really granular, half-formed ice (*névé*), mantled and bordered with recently gathered snow.

Movement of glaciers. — Most glaciers move with extreme slowness. Other things being equal, a glacier moves faster

FIG. 203. — Glacier des Grandes Jorasses and the Italian face of the Grandes Jorasses. Chain of Mont Blanc. (R. T. Chamberlin.)

when it is thick, when the slope of its surface is considerable, when its bed is steep and regular, and when its temperature is relatively high, than it does under the opposite conditions. The glaciers of the Alps move on the average a foot or two a day, while some of the great glaciers of Alaska and Greenland move several times as fast. Certain Greenland glaciers have been credited with the very unusual rate of 50 feet and more per day. From what has already been said, it is evident that glaciers move faster in summer than in winter. The ice of a glacier also moves more rapidly in the center at the surface, than along the bottom and sides (Why?). Since in the gathering

FIG. 204. — End of the Alsek Glacier, Alaska. (Netland, *U.S. Boundary Commission.*)

ground of a glacier the surface of the snow and ice is usually concave, the movement is inwards toward the center, as well as down valley. Farther down the valley, the surface is commonly convex, in part because the marginal ice is melted faster by heat reflected from the walls of the valley, and there is accordingly movement toward the sides of the valley, as well as along its axis.

FIG. 205. — The Zwillinge and Grenz Glaciers, Switzerland. Shows débris on the ice, crevasses, etc. (R. T. Chamberlin.)

The exact nature of the movement of glacier ice is a mooted question. The effect, so far as the form of the glacier is concerned, is much the same as in the movement of a thick mass of tar or wax. It is doubtful, however, if the motion is flowage.

FIG. 206. — Muir Glacier, Alaska.

Lower limits of glaciers. — Glaciers descend from their parent snow fields to a level so low and so warm that the wastage of the ice balances its forward movement. Many large glaciers reach far below the snow line; some of those in Switzerland end near grain fields and orchards. In high latitudes glaciers may reach the sea (Fig. 204). Turbid streams, fed by the melting ice, flow from the lower ends of many valley glaciers (Fig. 202).

Character of the surface of valley glaciers. — The surfaces of valley glaciers are in many cases notably irregular (Figs. 205 and 206). Varying in compactness, the surface ice melts unevenly. Changes in the slope of the surface down which the glacier moves cause the ice to crack open (Fig. 207). Where steep or precipitous descents occur in the bed, icefalls corresponding to waterfalls in rivers form, and the ice is often shattered by a multitude of cracks. Great cracks (*crevasses*) may be formed also by the more rapid motion of the center of the glacier, as compared with the sides. One or more crevasses, often large, sometimes form where the névé of the lower part of the parent snow field moves away

FIG. 207. — Portion of a glacier, showing crevasses in the ice due to changes in the slope of the bed.

from the thinner snows of the portion above. This fissure, or zone of fissures, where the glacier proper is sometimes considered as beginning, is called the *bergschrund* (Fig. 208). The

FIG. 208. — Bergschrund on east side of Fremont Peak, Wind River Range, Wyoming. (Baker.)

upper walls of crevasses formed in these or other ways, being more exposed to the sun and weather than the lower walls, melt faster, so that the openings often become conspicuously V-shaped, and are separated by a complex of crests and sharp ridges. Were it not for melting following cracking, most crevasses extending crosswise of a glacier would probably be closed by its onward movement. Rock débris weathered from the slopes above may accumulate in quantity on the ice. If such fragments are too thick to be heated through in the course of a day, they protect the ice beneath. The surrounding ice melting meanwhile, they come to stand on columns of ice (Fig. 209). Thin deposits of earthy matter such, for example, as wind-deposited dust, have an opposite effect. Dust absorbs heat faster than ice does, and thin deposits, heating through readily in the course of a

FIG. 209. — Rock-capped ice pillars. The rock retards the melting of the ice on which it rests, and the melting away of the surrounding ice leaves a pedestal.

FIG. 210. — The spreading end of a glacier, Alaska. (Brabazon.)

day, occasion the relatively rapid melting of the ice below. Depressions known as *dust wells* result. Miniature dust wells may often be seen in rapidly melting snow banks. Summer

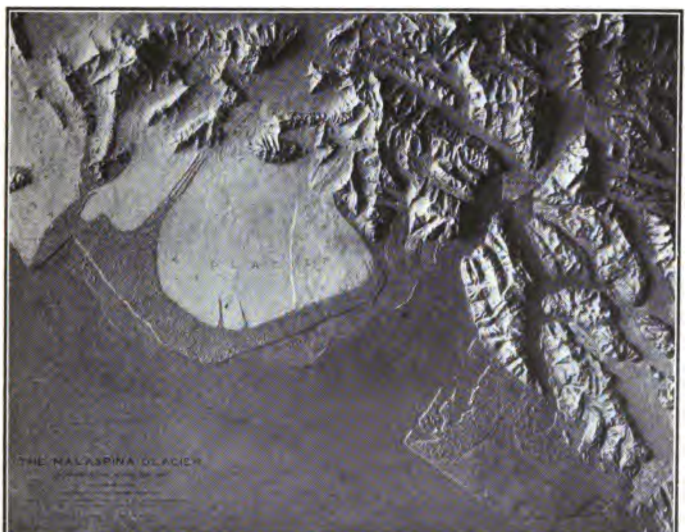

FIG. 211. — The Malaspina Glacier, and numerous valley glaciers. (Copyright by Univ. of Wis.)

melting of the surface ice in the lower portion of a glacier sometimes forms streams which cut ice valleys in the glacier. The above considerations help to explain the rough, broken surfaces of such glaciers as shown in Figure 206. Travel across them is difficult and often dangerous.

PIEDMONT GLACIERS

Unrestrained by valley walls, glaciers which extend beyond the mouths of their mountain valleys tend to spread (Fig. 210), and may come to occupy a considerable area. As already indicated, when several glaciers descending from neighboring mountain valleys spread out along the base of the mountains, they may unite to form a piedmont glacier. The Malaspina Glacier of Alaska is the type example of this class (Fig. 211). It is about 1500 square miles in extent (larger than Rhode Island), and its stagnant margin is covered deeply with rock waste which locally supports a dense forest.

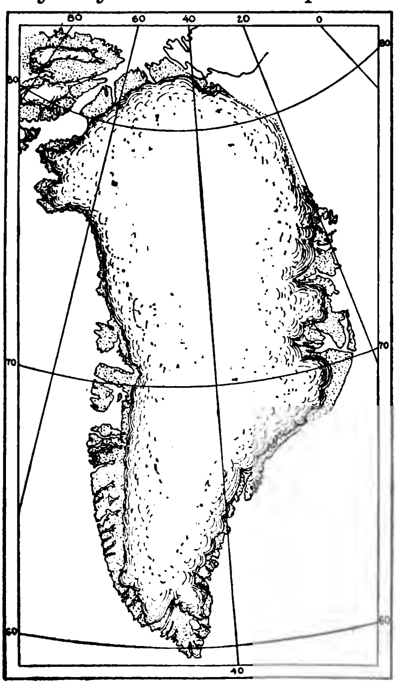

FIG. 212. — Map of Greenland ice sheet.

ICE SHEETS

Some ice sheets or ice caps are rudely circular, and others are irregular in form. The largest attain great size.

South polar ice sheet. — Antarctic explorers have made known the existence of a great ice sheet surrounding the

South Pole. Its area is not known, but it is believed to be more than 3,000,000 square miles (about the size of the United States, exclusive of Alaska). The ice moves slowly outwards toward the margins of the ice sheet, where great masses are detached as icebergs, and float away.

The Greenland ice sheet.—Save in a narrow, rugged coastal strip, all Greenland is covered deeply with ice and snow (Fig. 212). The area of the ice is probably some 400,000 to 500,000 square miles (seven to nine times as large as the state of Illinois), and its thickness toward the center more than a mile. Occasional mountain tops (called *nunataks*) rise as islands through its marginal portions. Close to its edge the ice contains many crevasses and carries more or less rock rubbish on its surface, but over the vast interior the surface is smooth and free from rock material. Thinning toward the coast, the ice sheet in places gives off great arms, which move along the valleys, often reaching the ocean. From the ends of these glaciers, some of which rise as cliffs 200 or 300 feet above the sea, great masses are detached, and floated away as icebergs (Fig. 213). Icebergs from Greenland are carried south by ocean currents and winds to the latitude of Newfoundland, and sometimes beyond. Rock material that was frozen in the glaciers is carried away by the icebergs and as they melt it is dropped on the ocean floor. Icebergs, however, are not important agents of transportation, and most of what they carry is soon dropped.

Fig. 213. — An iceberg.

Small ice caps occur on various Arctic islands.

Apart from the geological work which existing ice sheets are doing, and their climatic and other influences, they are interesting because they make it easier to understand the former existence of great ice sheets in regions now free from ice.

ANCIENT GLACIERS

In much of Canada, in the United States east of the Missouri River and north of the Ohio, and in northern Europe, the mantle rock consists of a mixture of bowlders, gravel, sand, and clay, ranging in thickness from a few inches to more than 500 feet. These materials occur separately in some places, and elsewhere are mixed confusedly in all possible proportions. This mantle rock was not produced by the weathering of the underlying rock, for in any given locality it contains material to which the decay of the bedrocks of that locality could not give rise. This fact is further shown by the contact between the

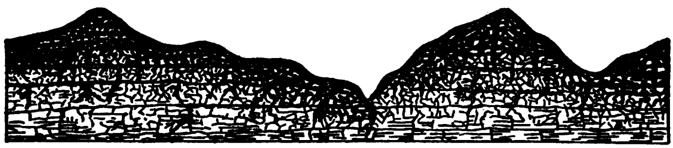

FIG. 214. — Diagram showing gradual transition from residual soil into the unaltered rock below. (*U.S. Geol. Surv.*)

mantle rock and the underlying rock. Mantle rock formed in place normally grades more or less insensibly into the firm rock below (Why? Fig. 214). In the areas in question, however, the surface material gives place abruptly in most places to the unaltered rock beneath as suggested in Figures 229 and 230. The mantle rock of these areas, therefore, was brought to its present position by one or more of the agents which transport materials upon the land. It is known as *drift*, the term having been applied under the impression that it had been drifted by waters to its present position from outside sources.

Figure 215 shows a typical exposure of unstratified drift (*till*). As shown in the illustration, till consists usually of material of many kinds and sizes, and is not in layers. The stones and bowlders are sometimes of kinds which do not occur as bedrock within many miles. Some of them are subangular in form and have flat faces, often highly polished and covered with minute scratches (Fig. 231). The drift

is often disposed unevenly, so as to occasion hilly belts and undrained depressions (Fig. 226 and Plate XII). The transporting agent, therefore, gathered its load from an area

FIG. 215. — Section of unstratified drift near Henry, Illinois. (Crane.)

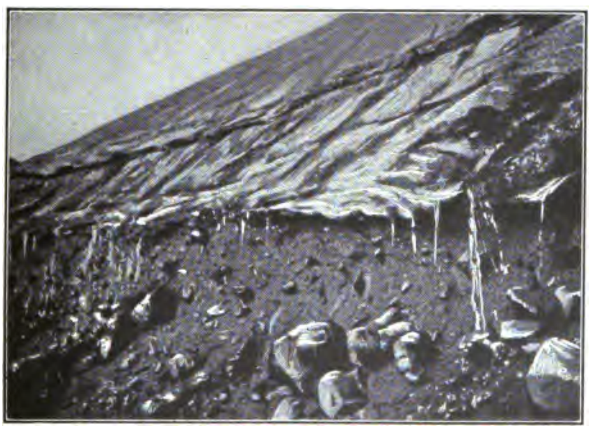

FIG. 216. — Shows the accumulation of drift beneath an existing glacier. Extremity of the lower Blase Dale Glacier of Disco Island, Greenland. (*U.S. Geol. Surv.*)

large enough to yield many different kinds of rock, and was capable of carrying large bowlders as well as fine clay, sometimes for great distances. It was capable, furthermore, of giving a part of the stones it carried the characteristics noted above, but was incapable of arranging its irregular deposits

FIG. 217. — Map showing the areas in and about the borders of North America covered by ice at the maximum stage of glaciation. The unshaded parts were covered by ice; the dotted portions were land areas free from ice. (Modified after Willis.)

in layers. It is evident that the transporting agent in question was neither the wind nor running water. The size of much of the material would at once exclude the former, while various considerations as effectually dispose of the latter. The largest bowlders of the till, weighing many tons, are far beyond the transporting power of common streams. Streams tend to round the stones rolled along their channels,

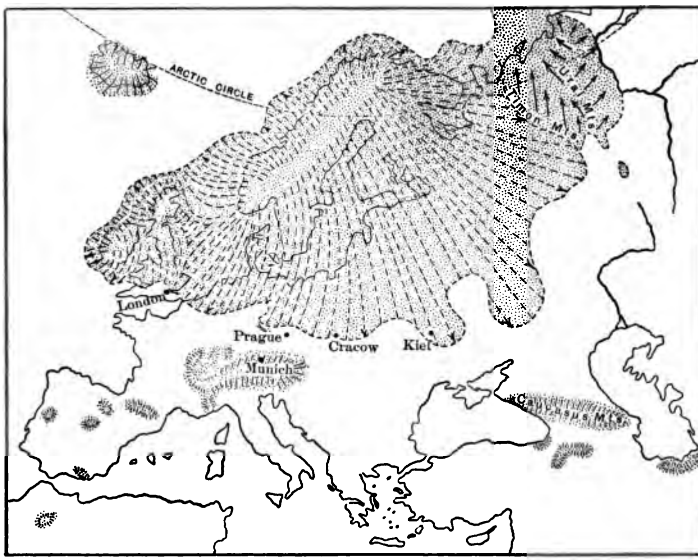

FIG. 218. — The shaded area shows the part of Europe covered by the continental glacier at the time of its greatest extent. (James Geikie.)

and are unable to develop flat faces. Stream-laid beds are in layers. The surfaces of water-deposited beds are without notable irregularities, such as often characterize the till.

Figure 216 shows deposits being made beneath a Greenland glacier that possess all the characteristics of those shown in Figure 215. So far as observed, all the deposits being made by existing glaciers show these same characteristics. Since existing glaciers are developing exactly the features belonging to the drift of the great American and

European areas referred to, and since no other agent is known capable of doing so, it has been concluded confidently that these regions were formerly covered by glacier ice. These glaciers were as extensive as the till is widespread, and therefore are known to have covered at their maximum development the areas shown in Figures 217 and 218. In a similar way other great areas in various parts of the world are known to have been glaciated at still earlier, but widely separated times (pp. 337, 394). Some of these areas are within the tropics, and now enjoy very warm climates. Glaciers are, then, one of the great geological agents that have modified numerous ancient as well as present land surfaces. Various phases of their work may be studied in most parts of northern United States.

The Geological Work of Glaciers

Like winds and rivers, glaciers transport rock waste, wear the surfaces over which they move, and deposit their loads to form characteristic features.

TRANSPORTATION AND DEPOSITION

As snow gathers to form a snow field it surrounds and covers loose pieces of rock on the surface, and incloses projecting ledges of firm rock. When the snow field becomes an ice field, and begins to move, it carries much of the loose material in its bottom with it, and may also break off and remove pieces of the bedrock, so that the glacier has a load from the beginning. Wherever the water in the soil upon which the glacier advances is frozen, it cements the soil particles into a firm mass. Wherever this ice-cemented soil is frozen to the glacier ice above, it becomes, in effect, a part of the glacier, and is likely to be carried on by its further movement. Most of the material carried by ice sheets, and possibly also much of that transported by many valley glaciers, is gathered in these and other ways by the under sur-

face of the ice. The material moved in the bottom of a glacier or lodged beneath it constitutes the *ground moraine.* The ground moraine deposits of the ancient ice sheets were

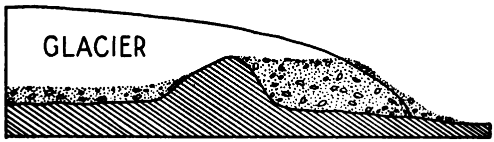

FIG. 219. — Diagram to show how débris in the body of a glacier may come to be on top through the lowering of the surface of the ice by melting.

frequently pressed by the weight of the overlying ice into very dense, compact beds. These are sometimes called *hardpan.*

Valley glaciers often carry heavy loads of rock débris on their surfaces. This is partly material weathered from the mountain slopes above, partly material worn from elevations in the bed of the glacier and brought to the surface by the melting of the ice above (Fig. 219), and partly also material

FIG. 220. — Moraine on south side of Hayden Glacier, in west-central Oregon. Note the constitution of the moraine. West Sister Peak, Cascade Mountains, in background. (Russell, *U.S. Geol. Surv.*)

brought up in other ways from the bottom. Belts of surface débris on the sides of valley glaciers are called *lateral moraines* (Figs. 220 and 221). If valley glaciers melt away, their surface lateral moraines are deposited on the valley floor beneath, along with material left by the bottom ice which moved from the center to the sides of the glacier (p. 198). In most cases the latter material makes up much

FIG. 221. — The Gorner Glacier with its feeders the Grenz, Schwarze, Breithorn, and Theodule Glaciers. Shows lateral and medial moraines, and the sources of the morainic débris. (R. T. Chamberlin.)

the larger part of the deposits. Lines of surface débris in or near the center are *medial moraines* (Fig. 221). In many cases medial moraines are the result of the union of two valley glaciers, whose adjacent lateral moraines have joined and occupy a medial position on the main glacier. Débris on the surface of a glacier near its head may be buried by accumulations of snow and carried forward in the body of the ice. Surface material may also work its way through

cracks in the ice toward or to the bottom. On the other hand, material may be brought in different ways to the surface of a glacier from a position within or beneath the ice, as noted above.

FIG. 222. — Sketch of a valley glacier in western Canada, showing terminal moraine.

Material carried at the bottom of a glacier may be dropped and picked up again many times before reaching a final resting place. Débris may lodge just beyond elevations over which the ice has passed. Moving vigorously over surfaces yielding material readily, the ice may obtain a load which later, under new conditions, it cannot carry. At its end, the moving ice is melting continually, the excess of forward movement over melting being the measure of its advance. Material obtained by the glacier back from its end will therefore, if not dropped, find itself sooner or later at the end, where it will be deposited as the inclosing ice melts. Overridden by the advancing glacier, it may be taken up once more, to be dropped again after a longer or shorter journey. Where the end of a valley glacier, or the edge of an ice sheet, remains essentially stationary for a long time, a heavy deposit results at and beneath the margin of the ice. This is called the *terminal moraine* (Fig. 222 and Plate XII). Obviously, the longer the margin of the ice remains stationary, the larger the terminal moraine becomes. Very massive terminal moraines left by ancient glaciers accordingly register very long stands of the margin of the ice. The terminal moraines of valley glaciers are more or less crescentic, the convex side pointing down valley (Fig. 222).

As already indicated, glacier deposits are unstratified, and consist commonly of materials of many kinds and sizes. Ice-ground clays usually retain the chemical character of

FIG. 223. — Drumlin near McFarland, Wis. (Alden, *U.S. Geol. Surv.*)

the parent rocks. Stream-borne silts, in contrast, are generally the product of weathering, and therefore differ chemically from the rocks from which they were derived. Melting ice has sometimes left great bowlders in seemingly insecure positions, forming "perched bowlders," "rocking stones," etc.

In some places till has lodged beneath ice sheets to form oval hills, called *drumlins* (Figs. 223 and 224). Drumlins vary in length from less than 100 feet to more than a mile, and in height from 15 or 20 to 150 or 200 feet. They are common in eastern Massachusetts, in parts of New York and Wisconsin, and in some other localities. In contrast with

FIG. 224. — Drumlin one mile northeast of Gleasondale, Mass. (Alden, *U.S. Geol. Surv.*)

ice-worn rock hills (p. 219), the shorter and steeper slopes of drumlins generally face the direction from which the ice sheets came.

The surfaces of glacier deposits are characteristic (p. 205).

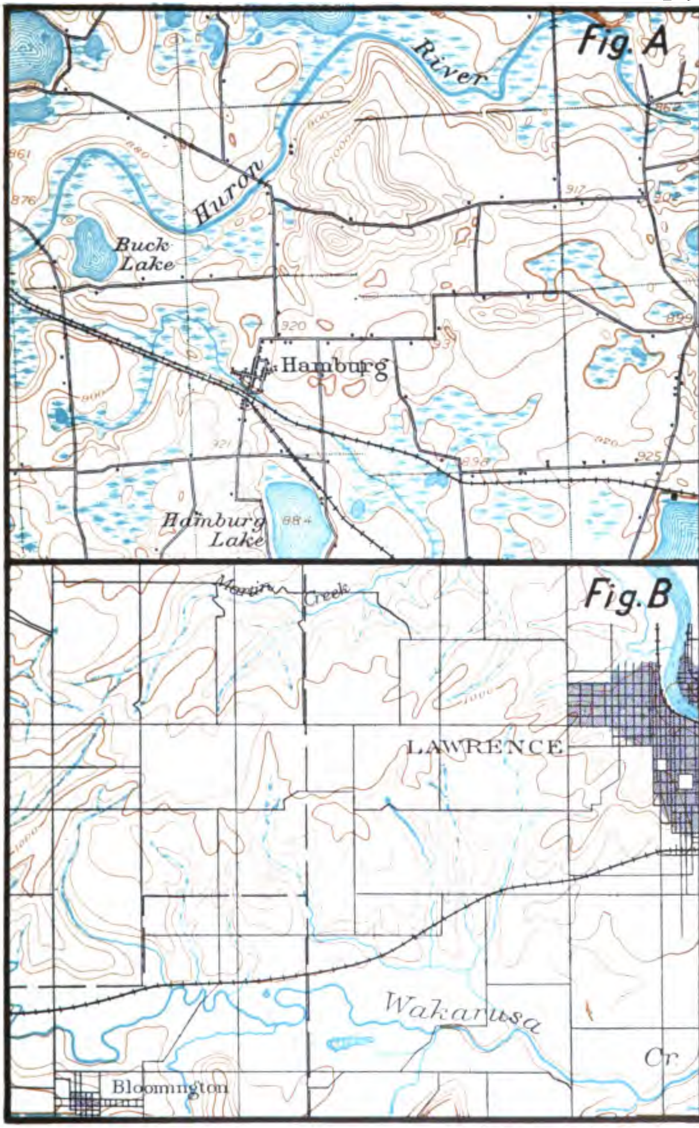

PLATE XI. Fig. A. Drift Topography. Contour interval, 20 feet. Scale, about 1 mile per inch. (Dexter, Michigan, Sheet, *U. S. Geol. Surv.*)
Fig. B. Topography developed by Stream Erosion. Contour interval, 50 feet. Scale, about 2 miles per inch. (Lawrence, Kansas, Sheet, *U. S. Geological Survey.*)

The drift is usually disposed irregularly, so that mounds and hills without systematic arrangement are associated with depressions of varying form and size, many of which have no outlets. The streams of recently (geologically speaking) glaciated regions commonly follow aimless and roundabout courses, and in many cases are interrupted by lakes and marshes (Plate XI, Fig. A). All this is in contrast with topographies due to river erosion. Since such topographies have resulted from the cutting of valleys, the elevations are distributed systematically with reference to the depressions, all of which have outlets (Plate XI, Fig. B). As we have already seen (p. 207), it is in contrast, too, with topographies due to stream deposition. The lake basins and other surface hollows of drift areas have been formed in several ways. Some are sections of preglacial river valleys in which drift was deposited unevenly. Where the ice deposited more material around than on a given area, the latter came to stand lower than its surroundings (Fig. 225). Still other basins were gouged out of the underlying rocks by the ice. The thousands of lakes in the northern part of the United States are practically all of glacial origin.

FIG. 225. — Section of a lake lying in a hollow of drift.

The features described above as distinctive of drift surfaces are most pronounced in terminal moraines, which are often characterized by notably hummocky topography (Figs. 226 and 227, and Plate XII). Numerous mounds, hillocks, and short ridges, ranging in diameter from a few feet to a half mile and more, and reaching occasionally a height of 100 to 200 feet, are associated with depressions varying in depth from inches to scores of feet, and in area ranging up to many acres. Many of the depressions contain ponds or lakes. Elevations and depressions are huddled together in confusion. Ground moraine surfaces are usually less

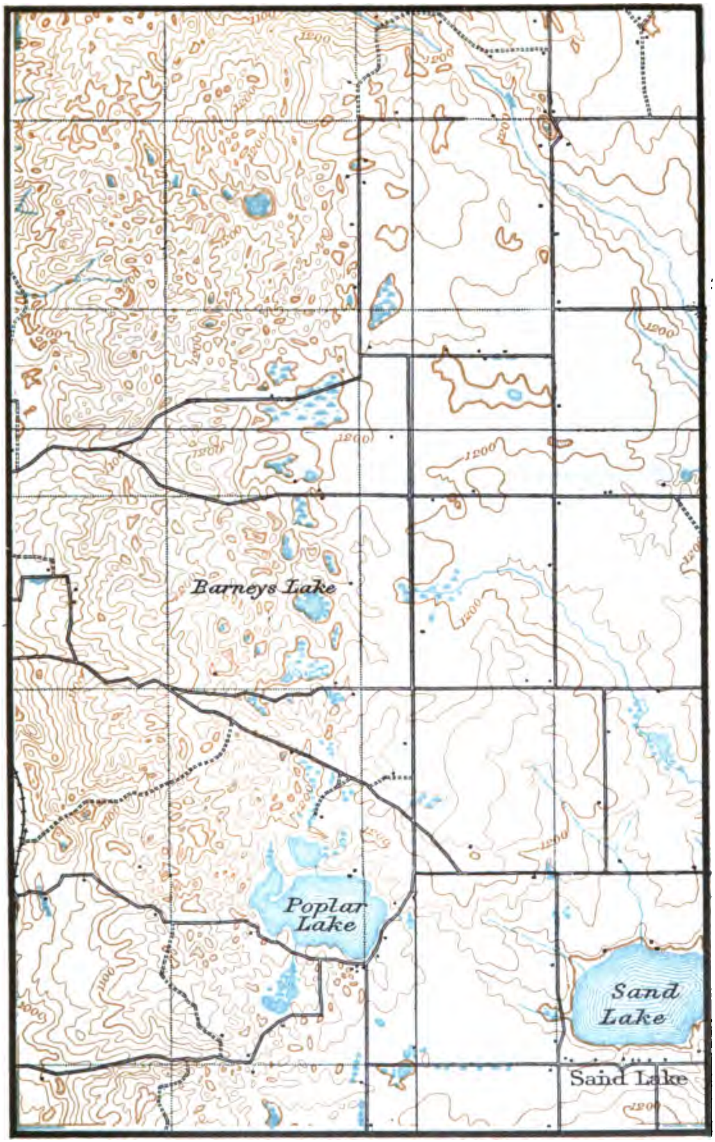

PLATE XII. TERMINAL MORAINE AND OUTWASH PLAIN. Contour interval, 20 feet. Scale, about 1 mile per inch. (St. Croix Dalles, Wisconsin-Minnesota, Sheet, *U. S. Geological Survey.*)

irregular. Hollows are not so deep, swells are not so high, and slopes are gentler. Certain ground moraine drift plains are almost flat.

FIG. 226. — Terminal moraine topography six miles southwest of Glenbuelah, Sheboygan Co., Wis. (Alden, *U.S. Geol. Surv.*)

The deposition of drift may render a surface rougher than before (Fig. 228), or may reduce the relief (Fig. 229).

FIG. 227. — Terminal moraine topography near Oconomowoc, Wis. The elevations are kames. (Alden, *U.S. Geol. Surv.*)

The latter seems to have been the result over most of the lake and prairie plains in northern United States.

TOPOGRAPHIC FEATURES DEVELOPED BY GLACIER EROSION

How glaciers erode. — Since it is much softer than rock, pure ice accomplishes little or no wear upon smooth, firm surfaces; rather is it worn by the harder rock. As already indicated, however, the bottom ice is likely to be charged with rock fragments, and thus armed, glaciers become efficient agents of erosion. Their rock tools are pressed with tremendous force upon the surfaces over and against which they move, and each kind does its appropriate work. Clay particles tend to smooth and polish, sand grains and hard pebbles to scratch (*striate*), and bowlders to gouge and groove the bedrock (Fig. 230). Meanwhile, the tools are themselves worn. The weaker ones may be ground into fine bits, even to rock flour. The stronger ones often are marked typically; their sides are worn flat, and, like the bedrock, are polished by clay and striated by sand (Fig. 231).

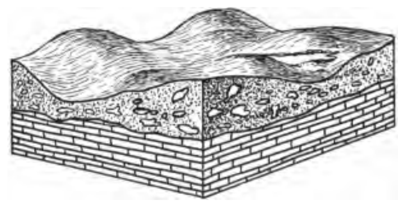

FIG. 228. — Diagram showing how a nearly level surface may be replaced by a rough one through the uneven deposition of drift.

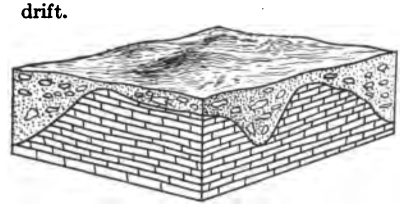

FIG. 229. — Diagram showing how glacial drift may be so disposed as to replace a hilly surface with a comparatively level one.

Thick ice moving over much-jointed surfaces sometimes quarries out blocks of rock by a process known as *plucking*. The bottom ice is pressed by the great weight of that above into the joints, bedding planes, and other openings of the rocks, and as the glacier moves onward, fragments, some-

FIG. 230. — Glaciated rock surface. The view shows also the relation of drift to the bedrock beneath. Northern Ohio. (Stauffer.)

times of considerable size, are dislodged. The freezing of water in the openings of the rocks beneath the ice helps in the process.

General effect of erosion upon relief. — Other things equal, ice sheets erode most in regions where many slopes oppose the advance of the ice. In flat regions the frozen mantle rock has sometimes been overridden by thick ice, and little disturbed. In rugged regions ice sheets tend to

FIG. 231. — Glaciated stones.

plane away the angularities of the surface, reducing and smoothing the slopes. Where hilltops are worn, the tendency is to reduce the relief. Where glaciers move along the axes of valleys, they tend to widen and deepen them, and so to increase the relief.

FIG. 232. — Lamberts Dome. A glaciated hill of granite. Upper Tuolumne River. (Fairbanks.)

Ice-worn hills and basins. — Hills that have been eroded vigorously by ice sheets are usually of characteristic form (Fig. 232). The side against and up which the ice moved (the *stoss* side) suffered most wear, and was lengthened and smoothed. The side away from and down which the ice moved (the *lee* side) is commonly the shorter and steeper, and was sometimes left rough and irregular by plucking. Where it crosses valleys and basins, and erodes them, an ice sheet usually wears chiefly the sides opposed to its advance, making them gentler and smoother (Fig. 233).

The shapes of glaciated rock hills and basins, then, record the direction of movement of ancient glaciers, the longer and smoother slopes facing the direction whence the ice came. Since minute projections and depressions are similarly shaped by the ice, the examination of any small surface of glaciated bedrock will usually show the direction in which the ice moved. (How much could be told concerning the direction of movement by the trend of the striæ?)

FIG. 233. — Diagram showing change which may be made in the cross section of a valley by an ice sheet which moves across it. Dotted line shows side of valley before glaciation.

Ice-shaped valleys. — Valley glaciers tend by erosion to widen and deepen their valleys and to steepen and smooth

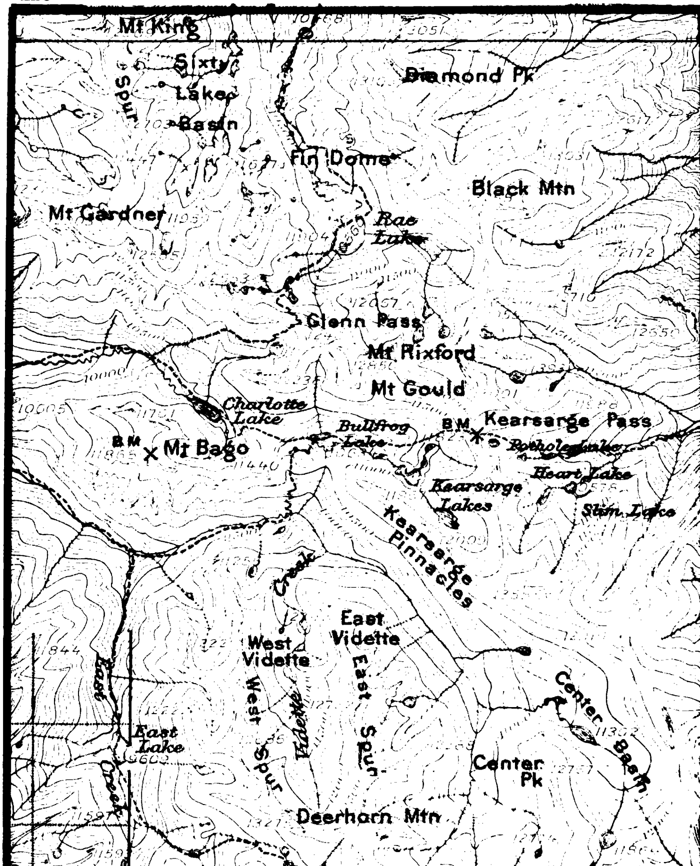

PLATE XIII. A Portion of the Sierra Nevada Mountains, showing Glaciated Valleys. Contour interval, 100 feet. Scale, about 2 miles per inch. (Mt. Whitney, California, Sheet, *U. S. Geological Survey.*)

their sides. Thus V-shaped valleys are changed to U-shaped troughs (Figs. 234 and 235, Plate XIII). The enlarged heads of glaciated valleys have broad bottoms, often containing ice-worn rock basins, and high, precipitous walls. Such valley heads are called *cirques* (Figs. 236 and 237, Plate XIII). In winter the névé and ice of the upper glacier freezes to the valley walls. In spring, the ice pulls away from them and dislodges and carries with it many rock fragments. During the summer the walls of the valley head may be more or less exposed to the agents of weathering, and material prepared for later removal by the ice. This process helps to drive the sides and head of the valley back into steep cliffs.

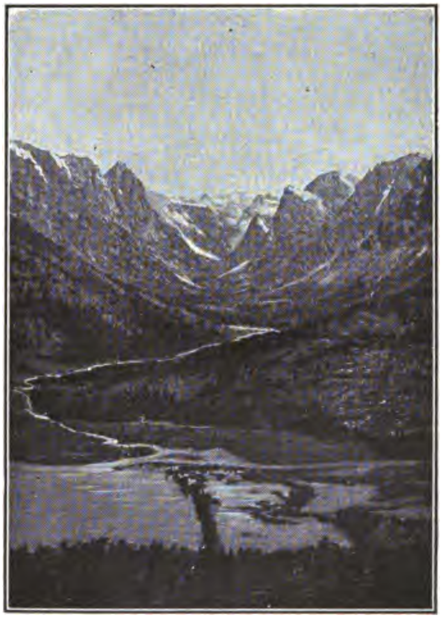

Fig. 234. — Glacial trough near Green River lakes, Wind River Range, Wyoming. Shows contrast between glaciated topography below, and unglaciated topography above. The lake in the foreground is held in by a morainic dam. (Baker.)

Lakes dot the bottoms of most glaciated valleys (Fig. 238, Plates X and XIII). Some of them occupy rock basins gouged out by the glacier (Fig. 239), and others fill depressions on the up-valley sides of morainic dams (Fig. 240).

Tributary valleys normally join their main valleys at even grade. But main valleys are often deepened by glaciers more than their tributaries. Because of this, and because

FIG. 235. — Glacial trough with hanging valleys. Upper cañon of Green River. (Baker.)

of the widening of the bottoms of the main valleys, the floors of the tributary valleys at their mouths are left standing higher (sometimes 1000 feet or more) than the opposite bottoms of the main valleys. After the disappearance of the ice, the streams of the tributary valleys descend in rapids or falls to the main streams. Such elevated tributary valleys are known as *hanging valleys* (Figs. 241 and 235). The same condition is of course brought about where a main valley is glaciated, while its tributaries remain free from ice.

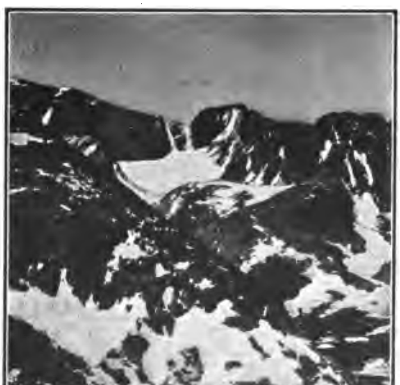

FIG. 236. — View in the Bighorn Mountains, Wyo. The cirque in the background contains Cloud Peak Glacier, which has a length of nearly a mile. The cirque walls are in places about 1500 feet in height. (Trowbridge.)

The topographic fea-

tures described above occur in western United States and Canada, among the Alps, and elsewhere, in many valleys now ice-free. They have been more or less modified, however, since

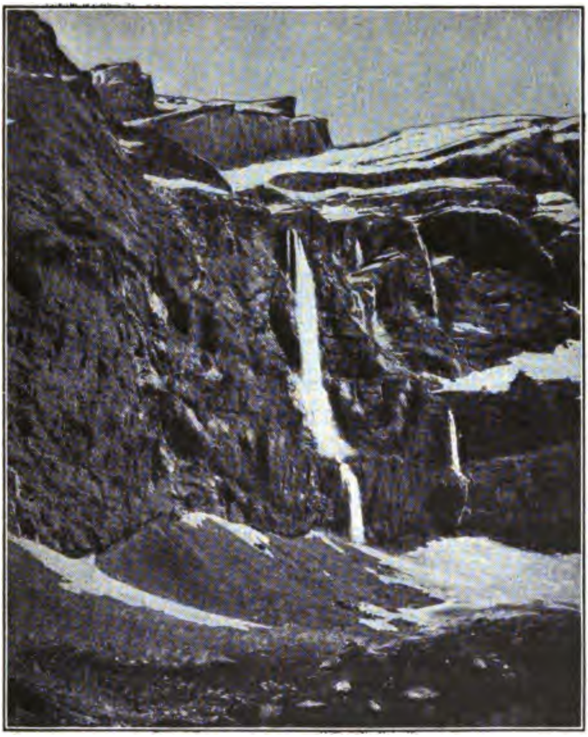

Fig. 237. — Near view of the walls of a cirque.

the disappearance of the glaciers, and will ultimately be destroyed. The glaciated rock surfaces not covered with drift are being weathered. The steep sides and heads of the valleys favor landslides, the accumulation of talus, and the formation of alluvial cones. The streams are grading the often irregular beds of the former glaciers, lowering the hanging valleys, and filling or draining the lakes. The relative extent of these changes in different valleys is a rough measure of the

FIG. 238. — Lakes of glacial origin in a mountain valley. The nearest lake is in an ice-scoured rock basin; the others are held in by drift. Note the U-shaped cross section of the valley in the middle distance. Piney Creek Valley, Bighorn Mountains. (Trowbridge.)

relative amount of time which has elapsed since the glaciers melted away.

Fiords. — Where thick glaciers push into the sea through narrow bays, they may scour the bay bottoms much deeper, and at the same time wear the bay heads back into the mainland. Where ancient glaciers have disappeared from such bays, the sea has entered to form long, narrow, steep-walled embayments, called *fiords* (Figs. 242 and 243). Typical fiords abound along the Norwegian, Alaskan (Fig. 244), and certain other high-latitude coasts. In most cases their depth is due partly to submergence of the coast. Many islands fringe these shores, representing for the most part higher land whose lower surroundings were drowned.

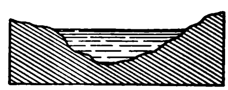

FIG. 239. — Section of a lake lying in an ice-scoured rock basin. Which way did the glacier move which formed this basin?

FIG. 240. — Section of a lake behind a barrier of drift.

The Work of Waters Associated with Glaciers

Water from the surface melting of summer and from rains sometimes forms streams that flow in valleys which

Fig. 241. — Hanging valleys, Lyngen Fiord, Norway. The hanging valley in the center contains a glacier. (R. T. Chamberlin.)

they have cut in the ice (p. 202). Water also finds its way through cracks and crevasses to the bottom to form sub-

Fig. 242. — Troldfjord, Lofoten Islands, coast of Norway. (R. T. Chamberlin.)

FIG. 243. — Fiord at North Cape, Norway. Photograph taken at 12.08 A.M., July 7, 1909. (R. T. Chamberlin.)

glacial streams. Subglacial waters are formed, too, by the melting of the bottom ice because of friction between the glacier and its bed, and in other ways. Ice-fed streams, in most cases heavily charged with gravel, sand, and silt, flow from the ends of valley glaciers, and at many points from the edges of ice sheets.

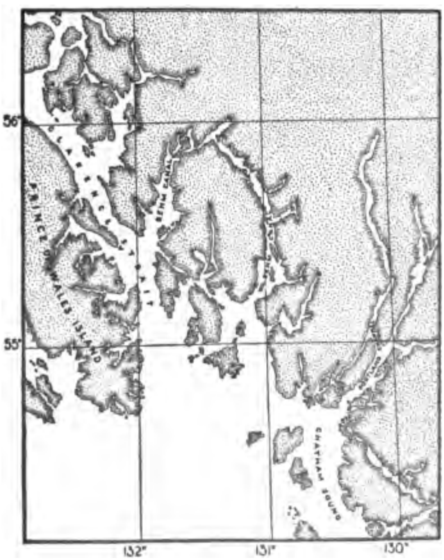

FIG. 244. — Alaskan fiords.

The streams beneath glaciers and beyond their ends and edges are commonly aggrading rather than degrading streams. Therefore the deposits made by glacial waters are the only matters in connec-

tion with their work which need be discussed. Like other stream-laid beds, such deposits are in layers and consequently unlike the till deposited directly by the ice.

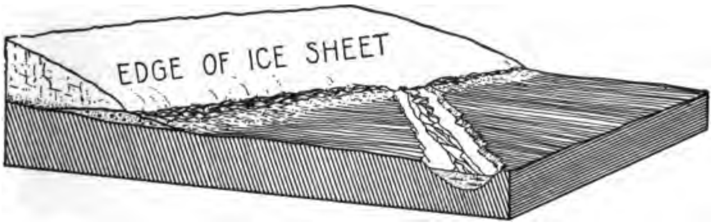

Fig. 245. — Diagram to illustrate the building of a valley train. Describe and account for what you see along the front of the ice sheet.

Valley trains. — Streams flowing away from glaciers in valleys of moderate slope are generally overloaded with débris derived from the ice and washed from tributary slopes beyond the ice. They therefore make deposits along their braided channels, building river plains of sand and gravel. Such aggradational plains are *valley trains* (Fig. 245). The stream deposits more and coarser material near the ice, and less and finer sediment farther from it. The downstream slope of valley trains is accordingly steepest near the ice and increasingly gentle away from it (Fig. 246). Much of the material of valley trains is cross-bedded.

Many remnants of valley trains, in the form of terraces, occur along the rivers of northern and northeastern United States. The longer the edge of the ancient ice sheet from

Fig. 246. — Diagram of a valley train, showing the slope of its surface, its structure, and its relation to the terminal moraine in which it heads.

which the aggrading streams issued remained stationary, the greater the valley fillings. Heavy valley train deposits, like massive terminal moraines, therefore indicate protracted stands of the edge of the ice.

Outwash plains. — Where overloaded streams that issued from the ancient ice sheet did not find valleys for their accommodation, as was often the case, they spread their material in fanlike deposits in front of the ice. Many such deposits made by neighboring streams often joined to form alluvial plains, known as *outwash plains*, which slope gently away from the terminal moraines which they front (Plate XII).

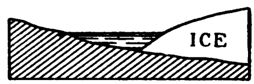

Fig. 247. — Section of a lake at the margin of an ice sheet.

Deltas. — Marginal lakes were sometimes formed at the edge of the ancient ice sheet where the land sloped downwards toward the ice, forming a temporary basin (Fig. 247). Where streams issued from the ice at the edges of lakes, they deposited their loads in the form of deltas. Such deltas are common in parts of New England.

Kames. — The edge of the ancient ice sheet was doubtless jagged and irregular (Why?). Subglacial streams, flowing in tunnels beneath the ice, were often under great pressure, like the water in a long tube. When such streams issued from beneath the ice in reëntrant angles of its edge, the pressure, and therefore their velocity and carrying power, were reduced. This caused them to make deposits, which were shaped by the partially inclosing ice walls. In this way irregular mounds and hillocks of rudely stratified and water-worn material were formed in association with the unstratified deposits of the terminal moraine. Such deposits are called *kames* (Figs. 248 and 227).

Fig. 248. — Kame east of Kewaskum, Dodge County, Wis. (Alden, *U.S. Geol. Surv.*)

Eskers. — Subglacial streams sometimes deposited sand and gravel along the floors of the ice tunnels through which

FIG. 249. — Bridgewater Esker, Rice County, Minn. (R. T. Chamberlin.)

they flowed. On the melting of the ice these deposits remained as serpentine ridges, called *eskers* (Fig. 249). Like the material of kames, that of eskers is usually rounded and poorly stratified (Fig. 250).

The bulk of the stratified material of the ancient drift sheets does not form distinct topographic features, but is scattered in irregular belts and layers within and beneath the till, as well as upon it.

FIG. 250. — Section of an esker near Randolph, Wis., showing its composition and structure. Many eskers are composed of much coarser material. (Miller.)

Summary

A chief function of glaciers is to return to lower and warmer levels moisture which otherwise would be imprisoned indefinitely as snow and ice. Geologically, glaciers, like rivers, have as their principal mission the wearing of the land and the moving of the waste toward the sea. In the aggregate, however, they are much less important agents of change than rivers. Streams are, and since the very early history of the earth have always been, at work nearly everywhere upon the land. Even in deserts there are very few large areas without valleys, although such valleys may be occupied only by temporary streams. At present, glaciers affect but a small fraction of the land surface, and while, as we have seen, their extent has been much greater than now at various times in the past, this was true, so far as known, for only comparatively short periods. Glaciers are at a disadvantage, too, from the fact that their work is entirely mechanical. On the other hand, their activities are not so conditioned by the hardness and structure of the surfaces upon which they work as are those of streams.

Although not so important geologically as they, ice takes its place with air and water as one of the three great gradational agents which modify land surfaces.

Questions

1. Why is the snow line much lower on the southern (sunny) side of the Himalaya Mountains than on the northern (shady and cooler) side?

2. Why have the Sierra Nevada and Cascade Mountains more glaciers than the Rocky Mountains? Why are there more in the northern than in the southern Rockies?

3. What are the factors upon which the size of a given valley glacier will depend?

4. What things limit the height which rock-capped ice pillars such as those shown in Figure 209 may attain?

5. Do all parts of the medial surface line of a valley glacier move at the same rate? Why?

6. In what part of a valley glacier should erosion be greatest? Least? Why?

7. (1) What will be the effect of the slow degradation of glacier-bearing mountains upon the snowfall they receive? (2) What influence will this have upon the position of the snow line? (3) How will the facts involved in the two preceding questions affect the size and length of the glaciers? (4) When will the mountains cease to have glaciers?

8. How could one determine in the field the approximate thickness of the glaciers which formerly occupied the valleys shown in Figures 234 and 235?

9. What conditions would produce valley trains (1) of high, and (2) of low average gradient?

10. Why are eskers usually roughly parallel with the direction of ice movement?

11. Compare and contrast typical topographies due to river erosion and to glaciation.

12. Moraine topography and dune topography are sometimes similar. How might the two be distinguished in the field?

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CHAPTER VII

OCEANS AND LAKES

Oceans and ocean basins. — The oceans have an area (143,000,000 square miles) nearly three times as great as that of the lands (54,000,000 square miles). They cover the low edges of the continents, so that their area is greater (by some 10,000,000 square miles) than that of the ocean basins. The ocean basins are a little more than twice as extensive as the continental plateaus. The submerged edges of the continental blocks are called the *continental shelves* (Fig. 251). The shallow seas on the continental shelves may be thought of as remnants of the vast, shallow seas which at various times in the past covered large portions of the continents.

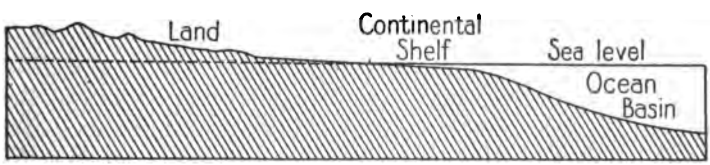


Fig. 251. — Diagram showing a continental shelf, and its relation to the land on one side and to an ocean basin on the other.

Soundings have shown that the bottoms of the ocean basins are generally smooth. Mountain chains and plateau-like swells are not altogether wanting, while great volcanic cones are numerous in parts of the Pacific Ocean, many of them rising as mountainous islands thousands of feet above the level of the sea. There are also submarine fault scarps and relatively small areas much lower than the surrounding ocean floor, called *deeps*. Nevertheless, these features occupy but a small fraction of the ocean bottom, nine tenths or

more of which forms a monotonously flat plain. As already indicated (p. 62), the absence of the familiar hills, valleys, and many other features of the land is due (1) to the fact that the bottoms of the ocean basins are protected from the attack of wind and weather, of streams and of glaciers, the agents which sculpture land surfaces, and (2) to the effects of the deposition of sediment in the ocean.

The average depth of the ocean basins is a little less than two and one half miles (about 13,000 feet). This is nearly six times the average elevation (some 2300 feet) of the lands above sea level.

Offices of the ocean. — (1) Nearly all the moisture which is condensed upon the surface of the land as rain or snow, or in less important forms, comes directly or indirectly from the ocean. Together with the atmosphere (p. 86), the ocean therefore makes possible the work of streams, of ground water, and of glaciers. Without the moisture which is evaporated from the ocean and carried by the winds to be precipitated over the land, neither plant nor animal life could flourish. This constitutes perhaps the greatest service which the ocean renders.

(2) The ocean tends to regulate the distribution of temperature over the earth's surface. The temperature of the winds is modified by that of the ocean surfaces across which they blow, and the heat or cold gained is carried over the land for greater or lesser distances. Warm ocean currents from low latitudes carry great quantities of heat poleward. Cold currents from high latitudes carry lower temperatures equatorward. Just as oceanic islands have more uniform climates than great land masses, so in past ages widespread invasions of the lands by the sea resulted in periods of uniform (*oceanic*) climate, while great extensions of the land areas coincided with periods of variable (*continental*) climate.

(3) In preceding chapters it has been pointed out that the ocean is the ultimate goal of all the waste of the land, which is spread out upon its floor as layers of sediment.

Throughout the geological ages a chief service of the ocean has been to receive, arrange, and preserve the materials from which new land areas were later formed. While aggradation has always been the dominant gradational process in the ocean, degradation has always been of chief importance upon the land.

(4) Finally, the sea has always been engaged in eroding portions of its shores. Thus it tends persistently to reduce the area of the land, and to increase its own extent.

The movements of sea waters. — The geologically important movements of the sea are wind waves, currents, and tidal waves. Earthquake waves and certain other occasional and unusual movements are at times important.

Wind waves are caused by the pressure of the wind upon the surface of the water. In the open sea, the water is pushed forward very little and slowly, even though the wave form advances with rapidity. Each particle moves through an elliptical path every time that a wave passes, but returns essentially to the point of starting. The movement of the water particles in a wave has been likened frequently to that in a field of tall grass across which the wind is blowing. Each blade is bent up and down, back and forth, yet retains its place. Waves are propagated with gradually lessening height far beyond the area of the storm which generated them; here the diminishing waves are called *swells*.

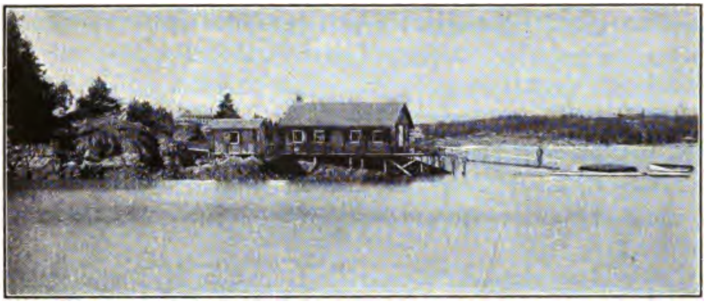
On approaching land, waves drag bottom and the oscillatory movement passes into a true onward movement. The unimpeded top of the wave moves faster than the lower part, which is retarded by friction with the bottom, and the front of the wave accordingly becomes increasingly steep, until the crest topples over and the wave breaks with all its weight upon the shallow bottom or upon the shore line (Fig. 252). The water of the broken wave rushes up the beach, and then returns seaward under gravity, forming the *undertow*.

The great ocean currents are caused primarily by the winds. Their courses are determined (1) by the direction of the winds, (2) by the arrangement of the land masses, (3) locally, by the configuration of the ocean bottom, and (4) by the earth's rotation, which deflects them toward the right hand in the northern hemisphere, and toward the left hand in the southern hemisphere. The importance of ocean currents in connection with the distribution of temperature has been referred to. Warm and cold currents influence greatly the present distribution of marine life, and the ocean currents of earlier geological periods, some of which flowed across the centers of the continents (then submerged), have to be taken into account in explaining the distribution of former life. The mechanical work of ocean currents is in general unimportant. Deep currents in shallow places may scour the ocean bottom, but the bottoms of currents are usually far above that of the sea. Certain ocean currents carry away sediment brought to them by the streams of the neighboring land, but large quantities are never carried far. (Why are ocean currents not so efficient transporting agents as rivers on the land?) The work of shore currents is discussed later (p. 246).

Fig. 252. — Breakers on the coast of California at Pt. Buchon. (Fairbanks.)

The regular rise and fall of the waters of the ocean, twice in about twenty-four hours, constitute the tides. In the open ocean the tides are imperceptible. Along the shores the change of level ranges from 2 or 3 feet to 50 feet and more in narrow bays. For about six hours the water rises and advances upon the shore (*flood tide*), and then for an equal time falls and recedes (*ebb tide*). Wide flats are in consequence often alternately exposed to the atmosphere and covered by the sea. In V-shaped bays and

estuaries, and in narrow passages between islands, tidal currents may be of great strength, and sometimes sweep quantities of sediment back and forth and erode the beds and sides of their channels. Tides aid the work of wind waves



Figs. 253, 254. — High tide and low tide on the coast of Maine at North Haven. The rocks exposed at low tide but under water at high tide are heavily covered with seaweed. Such vegetation often helps to protect rocky coasts against wave erosion. (Bailey Willis.)

by lifting and lowering them, and so increasing the width of their zone of attack (Figs. 253 and 254).

The Shores of the Ocean

The shores of the ocean are zones of great activity. Here is the meeting place of land and air and sea. The principal coast-line features and offshore deposits are discussed in

the following paragraphs. A knowledge of these things aids in determining the geographic changes of the past.

The characteristics of shore lines, and the agents which shape them. — The shores of the northern continents are characterized by great projections of the land into the sea, and by great extensions of the sea into the land. Large irregularities like Florida, Lower California, the Iberian Peninsula, and Hudson Bay are due to diastrophism. In a late geological period an upbowing of a part of the marginal sea bottom made an island of Florida which, by continued movement, was attached to the mainland as a peninsula. A geologically recent subsidence let the sea in over the area of Hudson Bay.

The submergence of a coast land having hills and valleys produces a new shore line which is irregular (Fig. 271). The drowned valley bottoms form bays, while the inter-valley ridges stand forth as headlands. Isolated hills of the old lowlands front the new coast as islands. Chesapeake Bay, Delaware Bay, and many other smaller bays along the eastern coast of the United States are drowned valleys or valley systems. On the other hand, the emergence of a coastal strip tends to produce an even, regular shore line, for the edge of the sea rests against the gently sloping former bottom (Fig. 255). (What should be the general height of new coasts due to (1) submergence, and (2) emergence?)

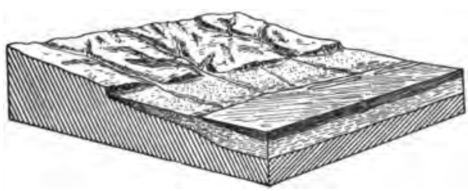


Fig. 255. — Diagram of a young coastal plain, with the old land in the background.

In addition to the features formed by diastrophism, many coastal irregularities are due to the work of gradational agents. Under normal conditions rivers erode but little at their mouths, but may build deltas into the sea (p. 185). Glaciers descending into the sea help to develop fiords

(p. 224), and may build islands by depositing drift. Loose material is often incorporated in ice formed along high-latitude coasts in winter; when the ice breaks up in the spring, this material may be carried away to be dropped where the ice melts. Weathering agents reduce sea cliffs and loosen material along shore, preparing it for removal by other agents. But most important in shaping the details of coast lines is the work of wind waves and of the shore currents which they generate. The features they develop are discussed below.

EROSION BY THE SEA

How the sea wears its shores. — Clear waves dashing against cliffs of firm, unjointed rock accomplish little or no wear. The inability of waves to erode under these circumstances recalls the similar dependence of winds, streams, and glaciers upon their rock tools. But the conditions suggested rarely occur. Usually the rocks of the seashore are traversed by joints. If stratified, they contain bedding planes. There are still other openings, and all form weak places. With the impact of strong waves, water is forced into the openings with great pressure. Furthermore, the air in the openings is compressed by the invading water, and then expands with force as the water withdraws. In these ways pieces of rock are broken and sucked off, and the openings enlarged. Ordinarily, too, the water offshore is sufficiently shallow for the waves to obtain from the bottom sand, stones, and sometimes, when very strong, even large bowlders, which are hurled as battering-rams against the shore. Locally, the sea dissolves the rocks of its shore.

Rate of erosion. — The rate at which a given coast is eroded is determined by several factors. (1) Other things being equal, strong waves obviously erode faster than weak ones. The velocity of the winds which generated them, the depth of the water they have traversed, and the distance they have

come before reaching the coast, all influence the strength of the waves. (How does each factor affect the result?) The force of waves has been measured in connection with certain engineering enterprises. On the coast of Scotland and among the outer Hebrides, storm waves sometimes exert a pressure of nearly three tons per square foot. (2) The rate

FIG. 256. — Wave erosion near Santa Cruz, Cal. The parallel channels in the foreground are the result of rapid wear along joint lines. (*U.S. Geol. Surv.*)

of wear is influenced by the character and structure of the rocks at the shore. Soft rocks wear faster than hard ones, soluble rocks faster than insoluble ones, rocks with many joints (Fig. 256) and openings faster than rocks with few. (Other things equal, which structure would occasion most rapid wear, (*a*) horizontal beds, (*b*) beds dipping abruptly toward the sea, (*c*) beds dipping away from the sea? Why?) (3) Finally, the rate of wear is influenced by the number and character of the tools of the waves. The shallower the water immediately offshore, the greater the number of tools that are likely to be accessible to the waves. But, on the other hand, if the water be very shallow for any considerable distance from the shore, the velocity of the waves will be so reduced by friction with the bottom that, on arriving at the shore line, they will be unable to erode effectively. It may be noted

that usually deep water fronts high coasts, and relatively shallow water, low coasts.

On the eastern coast of England, where the rocks are relatively weak, entire parishes have been washed away within a few centuries; in some places the shore line has retreated as much as 15 feet in a single year. The south shore of Nantucket Island, Massachusetts, has lost in places as much as 6 feet in a year, and as early as 1835 the opinion was expressed that within a few centuries the entire island would be devoured by the sea.

Sea cliffs and terraces. — The chief topographic effects of wave erosion are illustrated by Figure 257. The original slope near the water level is indicated by the dotted line. Eroding waves have notched this slope, forming a *sea cliff*. The development and recession of a sea cliff involve also the formation and widening at its base of an underwater platform, called the *wave-cut terrace*. Its surface represents the lower limit of effective wave action. It slopes gently seaward because, as its width increases, the strength of the waves at its inner edge decreases (Why?), and they are accordingly able to cut a less and less distance below sea level. (Should you expect the slope of wave-cut terraces to vary? If so, why?) At first the material worn from the cliffs is swept to the edge of the wave-cut terrace, and deposited in deeper water. Here it accumulates to form the *wave-built terrace*, which extends the wave-cut terrace seaward. Later, more or less of the waste of the cliffs remains here and there upon the terrace at their base (Why?) to form a beach. Still later, when the beach is developed more continuously, much of the waste is washed along it by waves and shore currents (p. 246). Wave-formed terraces may become land by lowering of the sea, or by uplift of the coast line (Figs. 258 and 259).

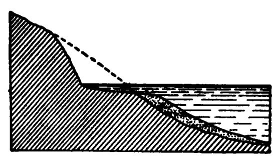


FIG. 257. — Diagram of sea cliff, wave-cut terrace, and wave-built terrace.

FIG. 258. — Wave-cut terraces on the California coast. (*U.S. Geol. Surv.*) How many terraces are shown? What is their relative age? Outline the history of the coast as recorded by the terraces. What changes are now in progress?

The height of sea cliffs depends upon the elevation above sea level of the land at the coast. Their steepness varies with (1) the strength and structure of the rocks, and (2) the rapidity of wave cutting and of weathering upon the cliffs above. Loose material usually cannot stand in steep cliffs. Firm rocks may form vertical and even overhanging cliffs

FIG. 259. — Raised beaches, near Elie, Fife. (Laurie.)

(Figs. 260 and 261). (What rock structures favor, and what ones oppose, the formation of steep cliffs?) Rapid cutting by the waves tends to keep the cliffs steep, while the weathering of the rocks of the upper cliffs and the removal of the loosened material tend to lessen their declivity. (What inference may be made from the fact that even sea cliffs containing

rocks capable of standing in vertical faces, commonly slope sharply back toward the land?) The rapid weathering of sea cliffs is favored by the absence of protecting talus (Why absent?) and often of vegetation, and by the frequently wet condition of the rocks due to the spray. The active issuance of ground water as seepage and springs near the level of the sea often helps to undermine sea cliffs.

FIG. 260. — Sea cliffs on the northern coast of France.

Sea caves, stacks, natural bridges. — The enlargement by the waves of a joint or other opening in the face of a sea cliff may result in a *sea cave* (Fig. 262), provided the overlying rock is strong enough to form a roof. Occasionally a sea cave is worn back and up to the surface of the ground some distance back from the cliff. Again, a fissure or joint may form an opening between the inner end of a sea cave and the surface of the ground. Storm waves sometimes drive spray and water up through such openings, which are then called *blowholes*.

Taking advantage of joint systems, waves sometimes quarry out the rocks about a section of a cliff, leaving it as an

island in front of the retreating shore. From their form, such islands are frequently called *stacks* or *chimney islands* (Fig. 263).

Waves may cut through a rocky headland in such manner as to form a *natural bridge* (Fig. 264). If the roof covering a

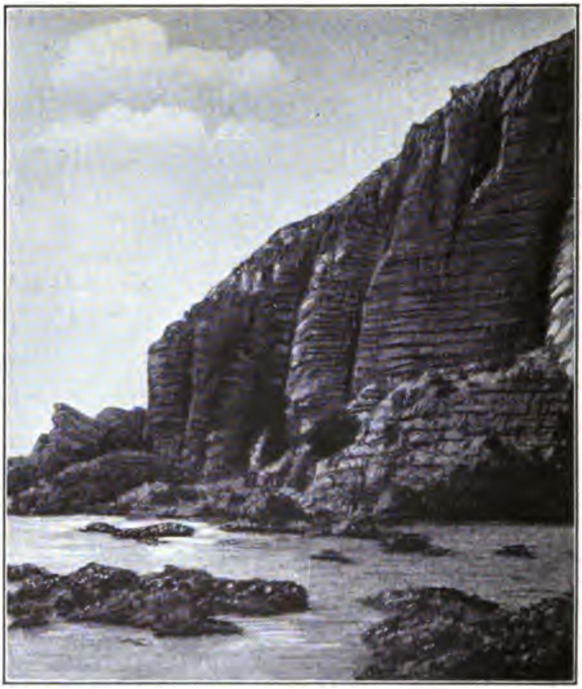


FIG. 261. — Sea cliffs in northwestern France.

sea cave near its mouth remains after the roof above the inner end of the cave has collapsed, a natural bridge also results.

While interesting because of their picturesqueness, these special features of cliff shores have little geological importance.

The goal of sea erosion. — Just as rivers seek to wear the land to sea level, so the waves of the sea, acting as a horizontal saw, seek to cut the land to a level slightly below the surface

of the sea. Extensive peneplains have been developed repeatedly in the past, but, so far as known, wave-cut submarine

FIG. 262. — Sea caves on the southern coast of California. (Fairbanks, *U.S. Geol. Surv.*)

When the upper cave was cut it stood in the same relation to sea level that the lower one now does. Since it was formed the land has therefore been elevated with reference to the level of the ocean.

plains of great extent have not been formed. This is because, as already indicated, waves drag bottom across the submarine flat which they cut, and so become weaker as the flat becomes wider. The gradual subsidence of a coast and marginal sea bottom aids in the extension of a wave-cut plain by gradually increasing the depth of the water upon it, and so maintaining the vigor of the waves at the shore. Gradual emergence, on the other hand, opposes the formation of an exten-

FIG. 263. — Stacks on the west coast of France.

sive wave-cut plain. Plains of marine denudation, like base-level plains, cut indifferently across beds of varying structure and hardness.

TRANSPORTATION AND DEPOSITION ALONG THE SEASHORE

The beach and transportation. — When waves come in to the shore obliquely, some of the bottom material is moved up and at the same time along the beach. Carried out by the undertow, it is again swept up and along the beach, and by a continuation of the process travels alongshore by a series of zigzag paths. Furthermore, winds blowing obliquely upon a beach generate a current which moves alongshore, and is known as the *shore current* or *littoral current.* Littoral currents are not strong, but when sand particles and pebbles are lifted wholly or partially by the waves or the undertow, the current is able to move them a slight distance along the beach in the direction of its movement.

FIG. 264. — Natural bridge on the coast of California, near Santa Cruz.

The beach is the roadway along which the shore drift is transported. (What determines its width?) The material of unprotected beaches at the foot of sea cliffs is coarse, for the water is agitated vigorously, and only relatively heavy material can remain; silt is carried seaward by the undertow, or along the coast by shore currents to more sheltered places. In sheltered bays and along low, protected shores, the beach material is likely to be fine sand or mud.

As the material of a beach is moved, sometimes to a depth of several feet on exposed coasts during severe storms, the particles are worn and crushed, and may be reduced at last

to fine mud. The final reduction of beach material is accomplished with extreme slowness, however, for the particles are becoming smaller and therefore lighter, and each is surrounded by a film of water, which acts as a cushion. All blows, therefore, come to be weak blows. Furthermore, before it is reduced completely, the material is apt to be removed from the mill of the beach, and deposited in quieter water. It is replaced by new material worn from the cliffs by the waves, or brought from the land by streams.

FIG. 265. — Hooked spit at entrance to Smithtown Harbor, Long Island. (Buffet.)

Features formed by deposition of shore drift. — When shore currents reach the entrance of a harbor, or some other abrupt bend in the shore line, they commonly continue in the direction in which they had been moving, instead of turning with the coast. They accordingly pass from the shallow water of the outer beach into deeper water, where they drop their load. The result is an embankment, known as a *spit*. Waves may build spits above sea level, and the winds may then form dunes upon them. Many spits accordingly present irregular surfaces, and support hills which rise 10 to 40 or more feet above sea level. Spits are tied at one end to the beach, of which, indeed, they form an extension, and are bounded by deep water at the free end. The ends of spits are frequently bent by storm waves. Bent spits are called *hooks* (Fig. 265). Occasionally the hook at the end is closed

FIG. 266. — A bar. Sea cliffs in distance.

completely, forming a *loop*. Many spits have been built entirely across the mouths of harbors, and joined to the beach beyond. Such completed spits are *bars* (Fig. 266). Bars sometimes connect islands with the mainland, thus making *land-tied islands*. Plate XIV shows spits, hooks, bars, land-tied islands, etc., on the coast of Long Island.

Barrier islands. — Storm waves drag on shelving bottoms at some distance from the shore. They drop most of their load where they break, along a line roughly parallel with the

FIG. 267. — Diagram of barrier islands and lagoon.

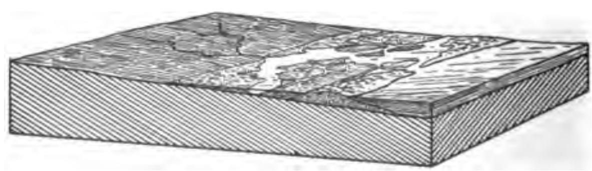


FIG. 268. — Diagram showing a later stage in the development of the coast represented by Figure 267. Dunes have formed on the barrier islands. Marshes cover much of the area of the lagoon.

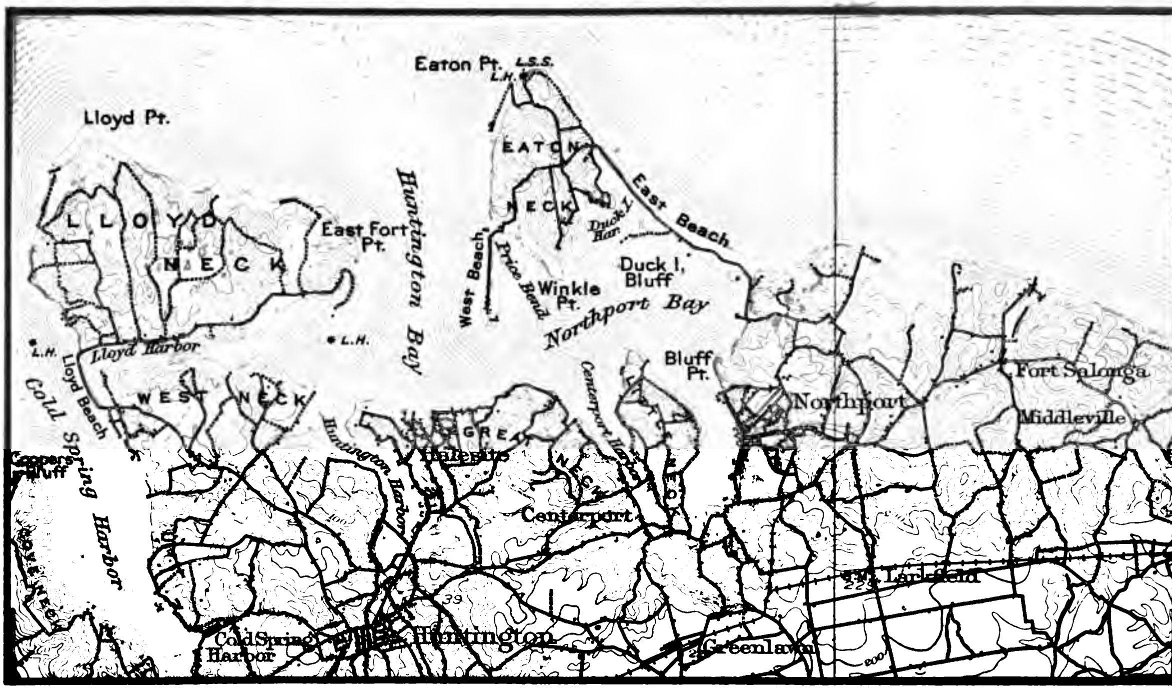


PLATE XIV. A SECTION OF THE NORTHERN COAST OF LONG ISLAND. Contour interval, 20 feet. Scale, about 2 miles per inch. (Islip, New York, Sheet, *U. S. Geological Survey.*)

shore. By this means, and also by the addition of material washed outward by the undertow, a ridge may be built above the sea surface, forming a long, narrow sand island called a *barrier* (Fig. 267). Dunes may presently be built upon its surface, and vegetation may obtain a foothold. Barrier islands extend along much of the coast of the United States from New Jersey to Texas. They inclose shallow-water areas called *lagoons*, which are being filled gradually by wash from the mainland and the islands, by migrating sand dunes and wind-borne dust, and by encroaching vegetation (Figs. 268 and 269). Thus lagoons may become marshes and finally be added to the mainland area. If, on the other hand, a barrier comes to receive less sand from the bottom or from other places alongshore than is carried away by waves and currents, it may be destroyed, together with the lagoon marsh it inclosed. Occasional breaks (*inlets*) in barriers are kept imperfectly open by tidal scour, by the outflow of waters from the mainland, or by both.

FIG. 269. — A portion of the New Jersey coast.

The tides of the Gulf of Mexico being weak, the barrier islands off the coastal plain of Texas have few breaks (Fig. 274), a fact which has retarded the commercial development of the region. Most lagoons are accessible only to boats of light draft, and are not frequented by extensive commerce.

Influence of plants and animals upon shore lines. — Plants affect shore lines in two important ways; they often protect

the shore against wave erosion, and certain plants which live in shallow salt water aid effectively in the extension of the land seaward.

Along a rocky shore one may often see at low tide that the rocks are covered with a mat of seaweed and other vegetation which, during storms, acts as a buffer to deaden the force of the waves (Fig. 254).

FIG. 270. — Mangroves on shore of Biscayne Bay, near Lemon City, Florida. (R. M. Harper.)

The mangrove flourishes on shallow, muddy bottoms off many low-latitude coasts not exposed to strong surf. Florida furnishes good examples (Fig. 270). The many widely spreading roots start from above the surface of the water and even from the lower limbs, forming a tangle which serves to catch and hold the sediment washed from the land. The effect of great numbers of trees is to occasion the lodgment of large quantities of sediment. Certain low, marshy coastal plains appear to have originated in this way. A similar work is done by grasses which grow in coastal lagoons and marshes.

STAGES IN SHORE-LINE DEVELOPMENT

Shore lines tend to pass through regular cycles of development. A coastal cycle is begun by diastrophism, emergence

tending to produce an even, regular coast, submergence an irregular one (p. 238). In either case, waves and currents tend first to increase the irregularity of the shore line, and finally to make it smooth. Unequal wave erosion and the building of spits, hooks, barriers, etc., increase the length of a shore line. Later, the wearing back of the headlands and the filling up of the indentations, the completing of bars and the filling in of the bays and lagoons they inclose, straighten and simplify the coast. Figures 271, 272, and 273 show successive stages in the development of an embayed (drowned) coast. Figure 274 shows shore deposits shutting in bays, and tending to simplify the coast line; thus far, however, they have increased the shore-line mileage.

FIG. 271. — Diagram of a coast that has been submerged recently.

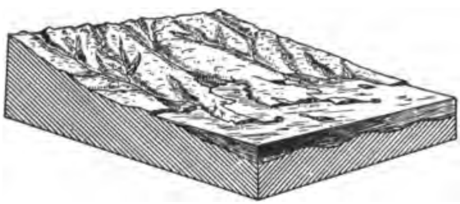


FIG. 272. — Diagram showing the coast represented by Figure 271 after it has been modified by streams and shore agents. Marshy bay-head deltas have been formed by the larger rivers. Waves have cut back the headlands in cliffs. Shore currents and waves have built hooks and bars. The islands are partly consumed. Submarine terraces front the cliffs. The material worn from the land is spread over the ocean-bottom as sheets of sand and mud.

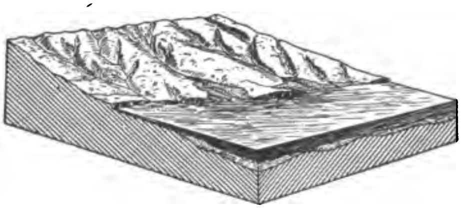


FIG. 273. — A still later stage in the development of the coast shown in the two preceding Figures. Bay filling and cliff recession have produced a nearly straight shore line.

There are several points of similarity between coastal cycles and the erosion cycles of rivers. First a river system roughens the surface of its basin, increasing its relief; finally it reduces it to a smooth plain, near sea level. As indicated above, waves and currents normally increase to a maximum the irregularities of a coast, and finally reduce them to a minimum. An essential difference is that the irregularities of the river basin are vertical irregularities, while those of the shore line are horizontal. In each case the cycle of development is introduced by diastrophism. Diastrophism in each case frequently terminates incompleted cycles.

FIG. 274. — Portion of the Texas coast, showing barrier islands and the tendency of shore deposition to simplify the coast line.

From what has been said already, it will be evident that the rate at which a coast develops depends on (1) the strength of the waves and currents, and (2) the resistance of the rocks of the coast. The outer coast of the end of Cape Cod is farther advanced than the inner, though the material is the same, because the outer side is exposed to the vigorous waves and currents of the open sea, while the inner side is somewhat protected (Fig. 275). The coast of Maine is in general in a youthful stage of development, though its exposure is comparable to that of the outer coast of Cape Cod, and waves and currents have worked upon it for nearly as long. The explanation lies in the fact that the material of the Cape Cod coast is loose glacial drift, while most of that of the Maine coast is resistant bedrock.

CHANGES IN THE RELATION OF LAND AND SEA

Sea level is geologically a critical level. It is the level to which the agents of degradation seek to reduce the land. The activities which are dominant on the land above it are different from those dominant in the sea below it. Great and repeated incursions of the sea upon the land,

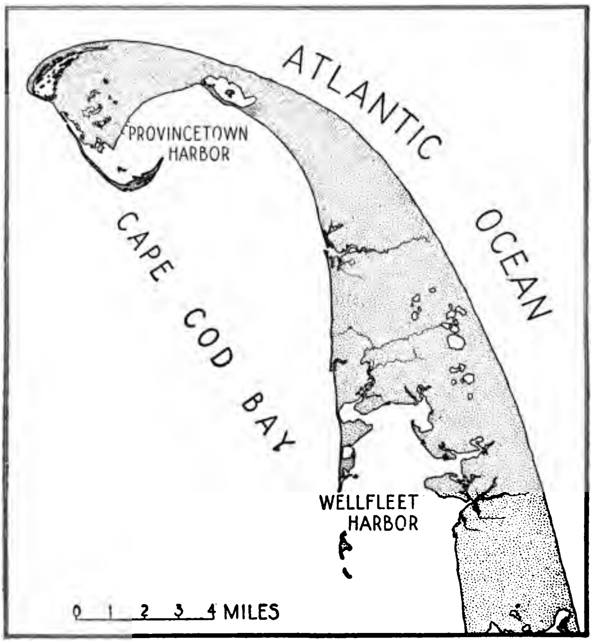


FIG. 275. — End of Cape Cod.

alternating with great extensions of the land at the expense of the sea, have been among the most important events in the past history of the continents, for they have changed the dominant processes over vast areas, have modified climates, and have changed the distribution and conditions of plant and animal life.

The causes of changes in sea level are several in number, aside from those changes due to waves, tides, etc., the geological effects of which have already been considered. Sediment from the land builds up the ocean floor, and so raises the surface of the sea. Submarine volcanic accumulations and the deposits of corals and shell-bearing sea life have the same effect. The elevation of a portion of the ocean bed would also raise the sea surface, while the down warping of a part of the sea floor would have an opposite effect. The lowering of a coastal area below the sea would, provided there were no movement of the ocean bottom to offset it, increase the area of the ocean, but lower the level of its surface. An increase or decrease in the aggregate amount of land water and ice would lower or raise the surface of the ocean. It has been estimated that if all the snow and ice on all the lands were melted and returned to the sea, it would raise the sea surface by some 30 feet. Since the oceans are all connected with one another, each of the above changes would affect the ocean surface everywhere and by an equal amount. In various other ways the surface of the sea is affected unequally. For example, coastal mountains attract the ocean waters, so that the neighboring sea surface is higher than that at a distance. Any notable change in the mass of a land area would accordingly affect the sea level. The above considerations help to explain the numerous changes in the distribution of land and sea that are discussed in the historical Chapters.

Ocean Deposits

LAND-DERIVED DEPOSITS

The great bulk of the land-derived deposits in the ocean was brought to the sea by rivers. The sea wears from its shores perhaps one thirtieth or one fortieth the quantity of material furnished by streams. Contributions which must become very important in the course of ages are also made by winds and by glaciers.

Distribution. — Fine dust from the land is carried by winds to all parts of the ocean. The deposition in the ocean of land-derived sediments is accordingly as widespread as the sea itself. This has undoubtedly been true ever since the oceans were formed. But most of the waste from the land settles within two or three hundred miles of the shore. Certain powerful river currents carry material much farther out to sea. The Kongo River, for example, is said to project its current 600 miles from shore, and the Ganges River nearly 1000 miles. Such cases are, however, very exceptional. The marginal sea bottoms are the great areas of sedimentation. The distribution of the important land-derived (*terrigenous*) deposits is shown by Figure 276.

Continental shelves. — Parts of the continental shelves (p. 233) may be to some considerable degree a product of the long-continued offshore accumulation of the waste of the land. Obviously, however, a continental shelf might be formed by the submergence of a coastal plain, due either to its depression or to an elevation of the surface of the sea. Soundings along the eastern coast of the United States and elsewhere have shown that valley depressions extend across the continental shelf from the mouths of various rivers. Since these valleys must have been cut above sea level, the sections of the continental shelf in which they occur appear to be due to the submergence of former land areas. Continental shelves may also be in part plains of marine denudation.

Character of land-derived deposits. — The more important points concerning both the character and the structure of deposits of land-derived sediments were noted in the discussion of sedimentary rocks (pp. 35–37). It will be remembered that the gravel, sand, and mud are shifted about and worked over by waves and currents, often for long periods before reaching a final resting place. In the process the materials are sorted, and beds of each kind result, which grade into one another both vertically and horizontally. Most of the gravel comes to rest close to shore in depths of 50 feet or less, but fine sand,

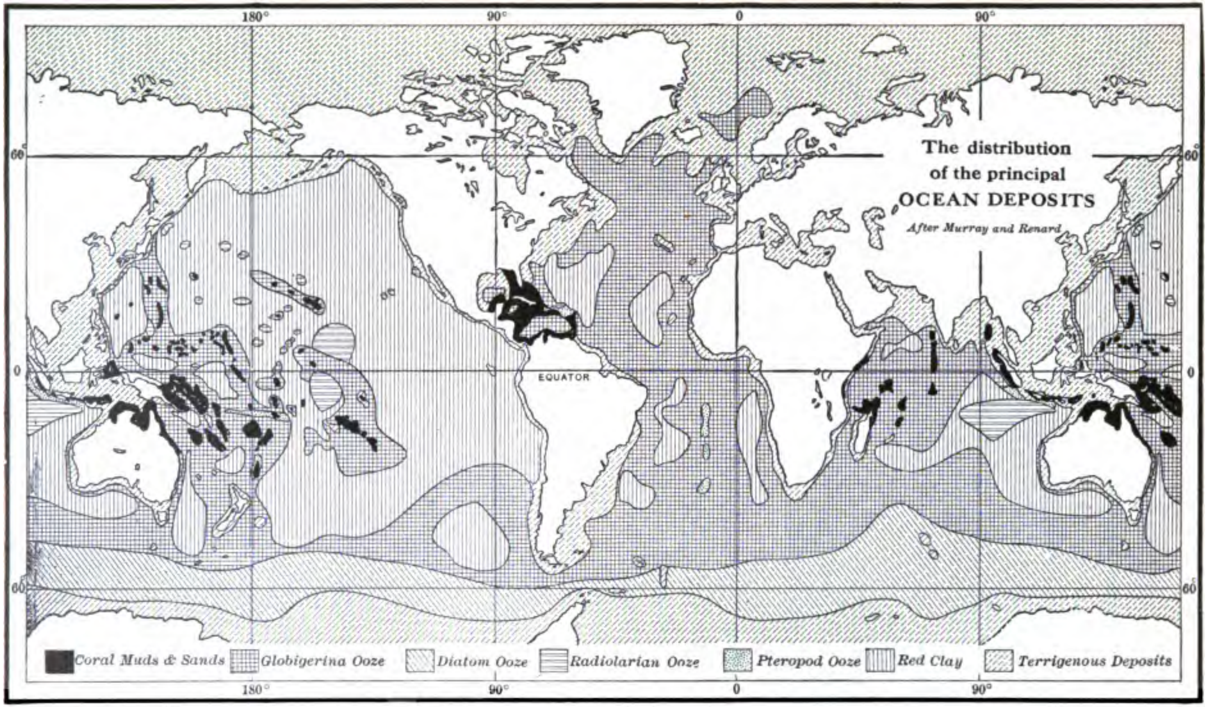


FIG. 276. — Map showing distribution of the principal ocean deposits. (After Murray and Renard, from Chamberlin and Salisbury's *Geology*.)

and even mud, find permanent lodgment in sheltered bays, and off low coasts where wave action is weak. On the other hand, coarse material may extend far out from shore, provided the water is shallow and the waves are strong. Most of the sand is deposited beyond the gravel, while beyond the sand fine muds are spread over the ocean floor to the limit of sediments brought by streams from the land.

Blue mud is the most extensive land-derived deposit, and is estimated to cover over 14,000,000 square miles of the sea bottom (nearly five times the area of the United States). It commonly contains tiny particles of numerous minerals, and is blue because the organic matter present prevents the oxidation of the iron. Red mud occurs over relatively small areas; here the clay contained so much Fe_2O_3 when brought to the sea that it has been only partially deoxidized. Green mud and greensand occur over an area equal to about one third that of the United States, and owe their color to the relatively large amount of the mineral glauconite present. Glauconite is a complex mineral containing alumina, potash, and iron. Extensive deposits of greensand now form part of the coastal plain of New Jersey.

ORGANIC DEPOSITS AND RED CLAY

Organic deposits are composed not of materials derived directly from the land, but principally of materials that were brought in solution by rivers to the sea, taken from solution in the sea water by plants or animals and built into their shells or other hard parts, and deposited upon the ocean bottom at the death of these organisms.

Oozes. — This term is applied to fine oceanic muds of organic origin. The various oozes are named from the organisms whose remains contributed most to the deposit. Often, however, the leading constituent of an ooze makes up only 20 or 30 per cent of the total deposit. *Globigerina ooze* (Fig. 277) is a calcareous deposit which takes its name from a

genus of Foraminifera, microscopic animals of extremely simple structure. Oozes of this class cover nearly 50,000,000 square miles of the ocean bed. The largest area is in the Atlantic Ocean (Fig. 276). *Radiolarian ooze* is also made up of the remains of a group of tiny, one-celled animals, but is composed of silica instead of calcium carbonate. It is confined, so far as known, to the Pacific and Indian oceans (Fig. 276). *Diatom ooze* is a siliceous deposit composed of the cases of minute plants known as diatoms. The largest deposit is in the Antarctic Ocean (Fig. 276). Various other deposits of similar origin receive special names.

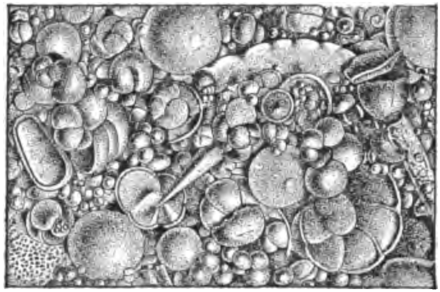


FIG. 277. — Globigerina ooze. Magnified about 20 diameters. (Murray and Renard.)

Coral deposits. — Reef-building corals are limited to ocean waters whose temperature does not fall below 68° Fahrenheit. They are restricted also to places where the water is clear and not over 100 feet deep. This confines them to the shallow areas of tropical seas, and prevents their growth off the mouths of large rivers where the waters are muddy. They thrive best where the water is agitated vigorously by waves and currents. This insures a continual supply of food, oxygen, and calcium carbonate, and removes the carbon dioxide. Reef-building corals live in colonies, many of which look like stubby plants. Each polyp consists of a fleshy, cylindrical sac with an opening at the top which serves as a mouth, and is surrounded with armlike feelers. Each polyp absorbs calcium carbonate from the sea water, and builds it into the stony framework which supports the colony.

Coral reefs are of several classes. Those extending along the shore and attached to it are *fringing reefs*. Those which

are separated from the shore by a channel or lagoon are *barrier reefs*. Rudely circular reefs inclosing a central lagoon are *atolls*.

Coral limestone is also of several kinds. As the reefs are built up toward the surface of the sea, they are eroded by the waves. The larger wave-worn fragments gather near the reef, and may be cemented into firm rock by the deposition of calcium carbonate from the sea water. Fine coral mud, ground up by storm waves, is deposited over wide areas at a distance from the reef, and when solidified forms a dense, fine-grained limestone. On coral beaches the sea water sometimes deposits concentric layers of calcium carbonate around particles of sand. A rock composed of tiny spheres that have been built up in this way is called *oölite*. Oölitic texture is produced also in other ways. Figure 276 shows the general distribution of coral muds and sands.

Since their appearance in an early geological period, corals have been important rock makers. Ancient reefs with all the characteristics of modern ones occur, for example, near Milwaukee, Wisconsin, and at Louisville, Kentucky, where they occasion the rapids in the Ohio River. The geography of these places at the time the corals lived may be inferred from the conditions which govern the present distribution of reef-building corals.

Red clay. — The most extensive ocean deposit, covering over 51,000,000 square miles, is known as red clay. It is characteristic of the deeper sea, remote from land (Fig. 276). Red clay consists in part of the insoluble residue of shells, and in part of the products of the alteration and decay of volcanic ash, dust, and pumice, which floats until it becomes waterlogged, and is drifted great distances by ocean currents. Fine dust from the land and from the combustion of meteorites during their passage through the air also contributes with extreme slowness to the deposit.

It is important to note that few, if any, of the rock systems of the land correspond to the deposits that are now making

in the deeper parts of the ocean, and that they do correspond to the sediments gathering on the continental shelves and in the relatively shallow seas.

Lakes

Distribution and origin. — Lakes range in size from tiny ponds a few feet across to Lake Superior, between 31,000 and 32,000 square miles in extent. They vary in depth from

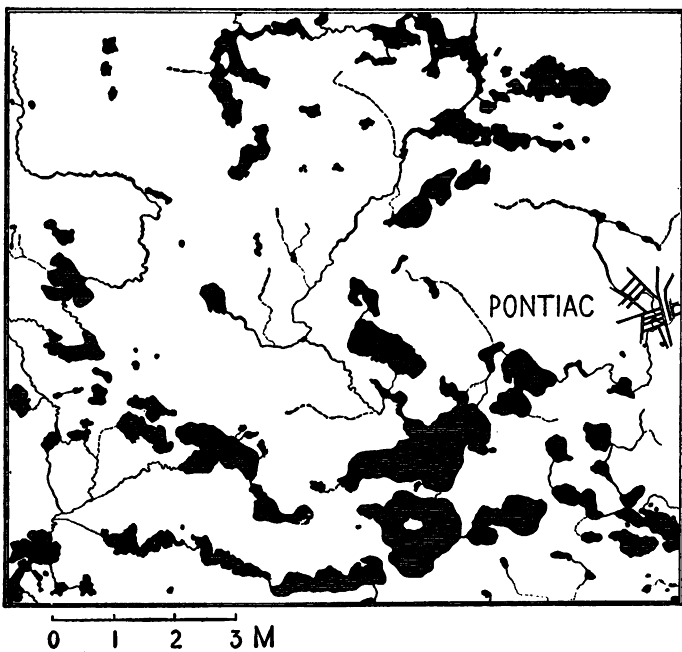


Fig. 278. — Lakes near Pontiac, Michigan. Illustrates the abundance of lakes in parts of the glaciated region.

inches to 5618 feet in the deepest part of Lake Baikal, in southern Siberia. Most lakes, however, are rather shallow. While they occur at all altitudes from below sea level to thousands of feet above it (the surface of Lake Titicaca is at

12,500 feet) and in practically every latitude, they are, nevertheless, distributed very unevenly over the surface of the land.

Lakes abound in the recently glaciated areas of northeastern United States, Canada, and Europe. Nearly one third of the surface of Finland is covered with lakes and marshes. Maine has 1620 lakes, and it is said that Minnesota may have 8000. Figure 278 illustrates their abundance in parts of Michigan. In these regions, as already indicated (p. 214),

FIG. 279. — Lake in an ice-scoured rock basin. Northern Washington. (Russell, *U.S. Geol. Surv.*)

they commonly occupy (1) ice-scoured rock basins, (2) hollows in the unevenly deposited drift (Fig. 225), or (3) the unfilled depressions of drift-choked preglacial valleys. Lakes are numerous also in northwestern United States, western Canada, the Alps, and elsewhere, in glaciated mountain valleys. Most of them fill depressions (1) behind morainic dams (Figs. 238 and 240), or (2) gouged out by the glaciers which formerly occupied the valleys (Figs. 239 and 279). Lakes are common

along many ocean shores, back of bars and barriers (Fig. 280). They occur in irregular belts or groups in certain interior basins and plateaus, as in central Asia and parts of Africa. Some of the larger lakes of these areas are in basins formed by the down warping or down faulting of portions of the surface (Fig. 281); some have formed behind dams of stream-swept waste; some have gathered in basins of other origin. Lakes are common features of many broad flood plains, representing abandoned sections of shifting rivers (p. 180). They are characteristic, too, of many large deltas (p. 186).

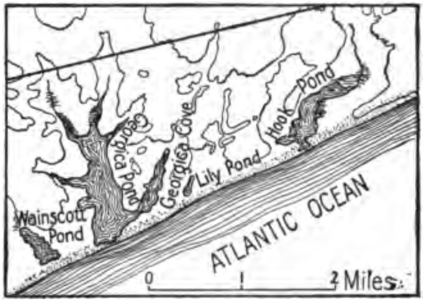


FIG. 280. — Coastal lakes shut off from the sea by sand bars. South coast of Long Island.

A few lakes occupy basins that have originated in still other ways. Avalanches and lava flows may dam rivers. The surfaces of recently emerged coastal plains may contain shallow depressions. Certain areas underlain by limestone have many sink holes (p. 118). These and other depressions may contain lakes.

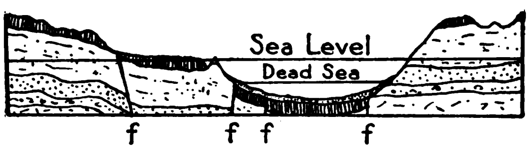


FIG. 281. — Section across the Dead Sea. *f f*, faults.

The general conditions necessary for the formation of a permanent lake will be inferred readily from what has already been said. They are (1) a depression below the surface of the surrounding country, (2) whose bottom is beneath the lowest level of the water table.

Functions of lakes. — The geological functions of lakes are several in number. (1) They tend to increase the rainfall and to equalize the temperature of their surroundings, making the summers cooler and the winters warmer than they would be otherwise. Since the character of the climate affects various geological processes, this tendency is not unimportant. (2) Mechanical and chemical deposits, discussed further below, are being made in lakes. Although but a few lakes are of great area (some ten only exceed 10,000 square miles in extent), yet the aggregate area of lake sedimentation is very large. (3) Lakes filter the waters of their tributary streams and regulate the volume of outflowing streams, preventing, or tending to prevent, destructive floods. Thus they influence erosion throughout the areas affected by the streams which flow from them. (4) Many kinds of plants and animals dwell in lakes, and the bodies of land-inhabiting animals are often washed in by streams. So far as these are capable of preservation, they may be converted into fossils in the growing lake sediments. Thus the lake deposits of former ages often afford a valuable record of the lake and land life of the times when the lakes existed.

Processes in operation in lakes. — The changes in progress in lakes correspond closely to those taking place in the ocean, and discussed in preceding pages. (1) Winds generate waves more easily in fresh than in salt water, because the former is lighter, and when lakes are sufficiently large and deep, strong storm waves develop. Where they wear the shore, cliffs and terraces are formed (Figs. 282 and 283). The material worn from the cliffs is swept by the undertow into deeper water, or transported alongshore by waves and wind-driven currents and built into beaches, spits, bars, etc. In the process the shore drift is assorted and worn. The general effect of the work of waves and currents is to increase the area of the lakes, but at the same time to make them shallower. (2) Streams and rains wash material into lakes from the tributary slopes. In many cases the sediment brought in by rivers accumulates at their mouths to form deltas. Lake deltas built

by mountain torrents are likely to be composed of coarse material and to have very steep fronts. (3) The slowly decaying

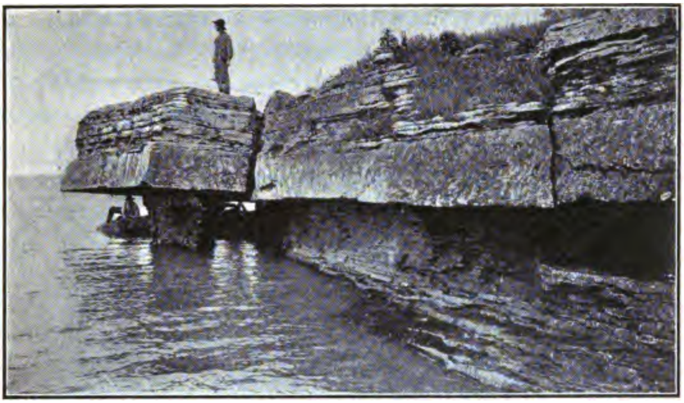


FIG. 282. — An undercut cliff on the shore of Kelleys Island, Lake Erie. (H. E. Wilson.)

remains of plants accumulate upon the bottoms of lakes, especially about their shallow borders, and tend to shoal them. (4) Various kinds of shell-building animals inhabit the waters of most lakes, and at death their shells help to fill the lake basins. (5) Winds blow some fine material into all lakes and much into many. (6) Certain minerals are deposited from the waters of many lakes, especially in arid regions. (7) Most lakes in humid regions fill their basins above the level of the lowest point in the rim, and so have outflowing streams. Such streams wear the outlets lower, rapidly when they are of large volume and the rock is soft, but very slowly when the

FIG. 283. — Sketch of the Bowsprit, Point aux Barques, Michigan. The island was formerly a part of the mainland, from which it was isolated by wave erosion. The waves are undercutting the island, and will destroy it in time.

rock is resistant, because, as noted above, lakes act as settling basins for the sediment brought in by their tributaries, so that the issuing streams have at the outset few tools. Still other less important changes are taking place in certain lakes.

The fate of lakes. — It is apparent from the foregoing discussion that lakes are short-lived features, and accordingly that all existing lakes are of geologically recent origin. Since deposits of every sort displace an equal volume of water, it is evident that if continued long enough, deposition will completely fill a lake basin and obliterate the lake. Vegetation is often a chief factor in the last stages of lake filling (Fig. 284).

Fig. 284. — A pond nearly destroyed by encroaching vegetation. Yellowstone Park. (Fairbanks.)

Furthermore, the outflowing stream may cut the outlet of a lake below the level of the bottom of its basin, and so drain off all the water. Most lakes are being destroyed slowly in both ways. It has been estimated that although Minnesota now has perhaps 8000 lakes, large and small, it will contain in fifty years fewer than 5000. Many of its lakes are really ponds, well-nigh effaced. This, of course, does not mean that the earth will presently be without lakes. Existing lakes will be succeeded by others, just as they have been preceded by many generations of earlier ones.

Extinct lakes. — Beds deposited in lakes now extinct cover extensive areas in various regions. Their origin is indicated by some or all of the following characteristics: (1) In many cases the beds show a concentric arrangement, the clays that gathered in the deeper and quieter waters in mid-lake being inclosed by the sand and gravel that accumulated about the shallower lake borders. (2) Except about the borders, where beach and delta structures may occur, beds laid in lakes are horizontal and often essentially uniform in texture over considerable areas (Fig. 285). This is in contrast with stream-

FIG. 285. — Lake-laid clays and fine sands. Near Devils Lake, Wis. (Trowbridge.)

laid beds (p. 40). (3) The beds may be bordered by shore features, such as spits, bars, cliffs, and beach ridges, although, save in arid regions, such features are soon destroyed by stream erosion. (4) Where fossils occur, they often indicate the character of the water body in which the associated sediments were deposited, since the life inhabiting fresh, brackish, and salt water differs. (5) Broad flats and mountain meadows may be so related to the inclosing slopes as to indicate clearly that they are the beds of former lakes.

Certain noted extinct lakes are referred to later (pp. 453, 458).

NONFRAGMENTAL DEPOSITS IN LAKES

The more important points concerning the distribution and structure of lake-laid beds of gravel, sand, mud, etc., are indicated above. The leading chemical and organic deposits of lakes may be described further.

Salt lakes. — Many lakes in arid regions lose as much or more water by evaporation into the dry air than they receive as rain on their surfaces and as run-off from the tributary slopes. Such a lake cannot maintain an outlet. Streams bring minerals into the lake, often calcium carbonate, gypsum, and common salt, which have been dissolved during the passage of the water through or over the rocks. As water is evaporated from the surface of the lake, these things are left behind, and as the process continues, the waters of the lake become more and more saline. When they become over-saturated, the minerals begin to be precipitated from solution. The deposition of calcium carbonate often precedes that of gypsum, which is followed in turn by common salt. Certain salt lakes and seas, such as the Caspian and Aral seas, represent portions of former arms of the ocean, now isolated by diastrophism. Such lakes begin their careers with the saltness of the sea. Most salt lakes, however, owe their salinity to the gradual concentration of salt leached by ground waters from the rocks and brought in by streams.

One hundred pounds of average sea water contain nearly 3½ pounds of mineral matter in solution, of which more than three fourths is common salt. The waters of many lakes are much salter than this. Those of Great Salt Lake, for example, contain about 18 per cent by weight of dissolved salts. This dissolved material is chiefly common salt, of which the lake is estimated to contain some 400,000,000 tons. Lake Van, in eastern Asiatic Turkey, contains 33 per cent of salt, and is the densest lake known.

Extensive salt beds which were deposited in ancient lakes

or arms of the sea are found interbedded with other rocks in various regions. Those in central New York may have an area underground of some 10,000 square miles (larger than Vermont), and individual beds are in places 80 feet thick. To form a layer of salt 80 feet in thickness would require the evaporation of some 6000 feet of sea water of average salinity. Clearly, the climate of New York must have been much less humid than now at the time the salt was deposited. Salt beds, like other deposits, therefore aid in determining the geography of the past. Their presence points to a period of aridity; their thickness suggests something of its duration.

Other chemical deposits. — While the deposits mentioned in the preceding paragraphs are perhaps the most common ones, many other substances are precipitated from the waters of certain lakes. For example, iron is precipitated so abundantly in some of the lakes of Sweden that it is of commercial value, and in the colonial period it was dredged from certain of the morainic lakes in eastern Massachusetts.

Marl. — Marl is a soft, limy clay, formed principally on lake bottoms. The calcium carbonate is contributed by the shells of fresh-water mollusks, by the decay of lime-secreting lake plants, and possibly in some instances by chemical precipitation. Only where little clay is washed from the slopes tributary to the lake is marl formed. Marl is used extensively for the manufacture of Portland cement.

Peat. — The formation of peat in flood-plain marshes has been noted (p. 178). Extensive peat deposits have been made also in shallow lakes and in the marshes which in many cases replace them. Peat deposits are most extensive in regions having moist and relatively cool climates, though by no means confined to them. A moist climate favors a heavy vegetation, and a cool climate retards its decay.

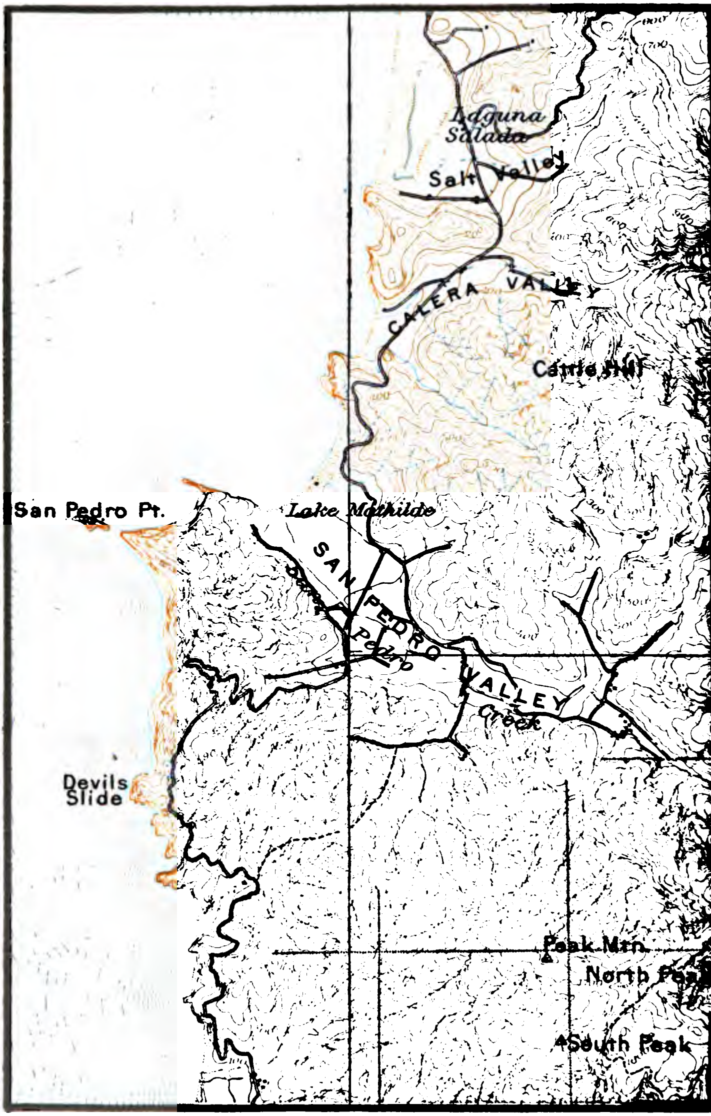


PLATE XV. A Section of the California Coast, a Few Miles South of San Francisco. Contour interval, 25 feet. Scale about 1 mile per inch. (San Mateo, California, Sheet, *U. S. Geological Survey.*)

QUESTIONS

1. How may the fact that a given beach grades regularly from coarse gravel at one end to fine sand at the other be explained?

2. Why is there generally a larger percentage of elliptical pebbles along beaches than along stream beds?

3. (1) What was the origin of the long, narrow peninsula shown in Figure 286? What is it called? Why does it not extend entirely across the bay? (2) What is the prevailing direction of the littoral currents along this shore? How is it shown? (3) Account for the triangular marshy tract on the northeastern side of the bay. (4) What seems likely to be the future history of the bay? What are the several agencies which will assist in bringing it about?

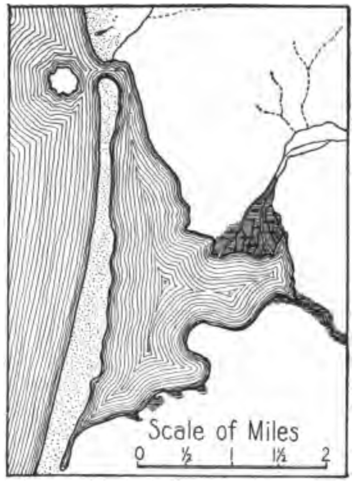


FIG. 286. — Map of Morro Bay, coast of California.

4. Plate XV. (1) Where along this shore is erosion in progress? (2) Is deposition anywhere in progress? (3) What is the probable explanation of the irregularities of the coast line in the vicinity of Devil's Slide? (4) Why are parts of the coast high, and other portions low? (5) What was the probable origin of the island off San Pedro Point? (6) Explain Lake Mathilde and Laguna Salada. (7) What changes may be expected in the character of this coast line in the future?

5. What inferences may be made from the fact that the beach lines of certain extinct lakes are not horizontal?

6. (1) Why is the ocean salt? (2) Why are broad, shallow lakes more likely to become salt than deep, narrow ones?

7. The size of certain salt lakes is decreasing. Does it follow (assuming that the climate remains the same) that these lakes will finally dry up?

8. Account for the fact that borings about salt lakes have often shown layers of salt alternating repeatedly with layers of clay.

9. Are the waters of coastal lakes that are separated from the ocean by bars generally fresh or salt? Why?

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CHAPTER VIII

THE GREAT RELIEF FEATURES OF THE LAND

MOUNTAINS, plateaus, and plains have been referred to frequently in previous pages. The more important points concerning their origin and life history are summarized in the present Chapter. Most of the geological processes and agents are concerned in their formation and development. The present characteristics of any given relief feature are determined chiefly by (1) the method of its formation, (2) its original altitude and its distance from the sea, (3) the character and structure of its rocks, (4) the character of the agents of erosion that are slowly wearing it down and the conditions which govern their work (especially the nature of the climate), and (5) the stage in their work which the erosive agents have reached.

MOUNTAINS

A mountain is an elevation which rises prominently above the surrounding country, and which has a comparatively small area on top (Fig. 287). On a low, flat plain, a mountain may have a height of only a few hundred feet; in more rugged surroundings, a much higher elevation may be called a hill. The matter is therefore a relative one, and no fixed height is necessary in order that an elevation may be classed as a mountain. Certain plains — for example, the western portion of the Great Plains — are higher than many mountains, — for instance, the northern Appalachians (Figs. 43 and 44, pp. 62 and 63). Most mountains, however, are higher than most plateaus and plains. A few of them reach elevations above sea level of nearly 30,000 feet, or about 5½ miles.

Compared with the diameter of the earth, even the loftiest mountains are insignificant protrusions of the lithosphere.

Mountain ridges and peaks are grouped commonly in relatively long and narrow belts, called *mountain ranges*. When several more or less parallel ranges are grouped together, they constitute a *mountain system*. Thus, one speaks of the Wasatch Range of Utah, but of the Rocky Mountain System.

Distribution of mountains. — It is noteworthy that mountain ranges are situated in general near the edges, rather than in the interiors, of the land masses. It is striking, also,

FIG. 287. — Mountains rising conspicuously above an aggraded plain. Alaska. (Netland, *U.S. Boundary Commission.*)

that most of the loftiest mountain chains are not far from the shores of the greatest sea, the Pacific Ocean. In a general sense, the land masses accordingly have two very unequal slopes, a short and relatively steep one toward the Indian-Pacific, a long and gentle one toward the Atlantic or Arctic Ocean. What is most significant probably is that most mountain chains are near the junctions of the continental plateaus and the ocean basins, and that most of the longest and highest ones are near the edges of the greatest basin. The settling of the larger and heavier ocean basins, due to the cooling and consequent contraction of the earth, possibly may have been an important cause of the deformation of the

edges of the smaller and lighter continental plateaus. The matter is, however, an unsolved problem.

The leading types of mountains are noted below.

Faulted (block) mountains. — Figure 288 shows several mountain ridges, and suggests their origin. A plateau or plain was divided by fissures into a series of great blocks, which were displaced by faulting, the relatively elevated edges forming mountain ridges. The mountain ridges may owe their relief to their having been uplifted, or to the sinking of the lower land, or to both. Such mountains are called *faulted* or *block mountains*. The mountains shown are still young, for their crests are without notches, and streams have not carved valleys in their even slopes; little talus has accumulated at the base of the great fault scarps. The smooth

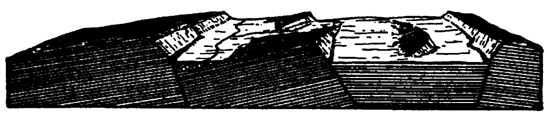

FIG. 288. — Diagram of block mountains.

slopes show also that the surface from which the mountains were formed was essentially level, and therefore topographically either young or old. The ridges diminish gradually in elevation from the points where the vertical displacement of the beds was greatest, and die out where the faults end. The beds dip away from the fault scarps.

As time passes, streams will dissect the now smooth slopes. Later, the larger valley bottoms and finally even the strongest inter-valley spurs will be worn down to base level, unless the mountains are maintained by further diastrophism. Buried beneath the waste-mantled surface of the resulting plain, the fault planes and tilted beds will record the former existence of the mountains.

Young block mountains 1000 or 1200 feet high and 10 to 30 or 40 miles long occur in southern Oregon and the adjacent states. In Nevada there are block mountains now

maturely dissected. There are many faulted mountains in the Great Basin region, where they are perhaps the leading type of mountain structure (Fig. 289).

FIG. 289. — Diagram showing the general arrangement of block mountains in the Great Basin. Each mountain block is tilted in the direction indicated by the light slanting lines. The broken lines show the profiles of the mountains before erosion. The dotted portions of the diagram represent the accumulation of waste. Length of the section, 120 miles. (Gilbert.)

Folded mountains. — Mountains consisting of a series of earth folds are a common type. In the Jura Mountains of France and Switzerland, open, symmetrical anticlines form parallel ridges, separated by synclinal troughs (Fig. 290). The structure of most folded mountains is much more com-

FIG. 290. — Diagram showing symmetrical folds of the Jura Mountains.

plex than that of the Juras. In parts of the Appalachians, for example, the folds are closed, unsymmetrical, and often overturned, and the structure is complicated by many faults, some of which have a vertical displacement of several thousand feet (Figs. 291 and 292). Here the strata were sub-

FIG. 291. — Structure section in the Appalachian Mountains. Southwestern corner of North Carolina. (From Nantahala, N. C. — Tenn., Geologic Folio, *U.S. Geol. Surv.*)

jected to much greater compression than in the Jura Mountains. Most of the strike faults in folded mountain regions are overthrusts (Why?). Where the folding of the beds was intense, the larger folds are composed commonly of a diminishing series of minor folds (Fig. 291), the smallest of

which may be of microscopic size. Compression tends also to metamorphose the rocks, and usually the amount of change which they have undergone corresponds to the intensity of the folding.

The present topography of most folded mountains — for example, of the Juras and Appalachians — is not controlled by

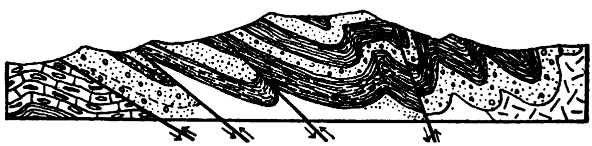

FIG. 292. — Structure section in the Appalachian Mountains. Eastern Tennessee, western North Carolina. (From Greeneville, Tenn. — N. C., Geologic Folio, *U.S. Geol. Surv.*)

the original folding and faulting, but by subsequent erosion and diastrophism. In many cases the crests of the anticlines were weaker than the synclines, for their rocks were stretched by the folding, and joints and other openings were widened, while the rocks of the synclines were compressed and strengthened; and so the anticlines have often come to form the valleys, while the synclines, originally the valleys, constitute the

FIG. 293. — Cross section of a portion of the Appalachian Mountains, showing synclinal ridges and anticlinal valleys. (Rogers.)

ridges (Fig. 293). The development of the present topography of the Appalachian Mountains (Plate XVI) was discussed in a general way on page 153 in connection with cycles of erosion.

It is particularly to be noted that the formation of folded mountains, and indeed of all mountains, is an extremely slow process, probably occupying, in the case of the greater ranges, hundreds of thousands or even millions of years. Many mountains appear to be growing now, — for example the Sierras and the St. Elias Range.

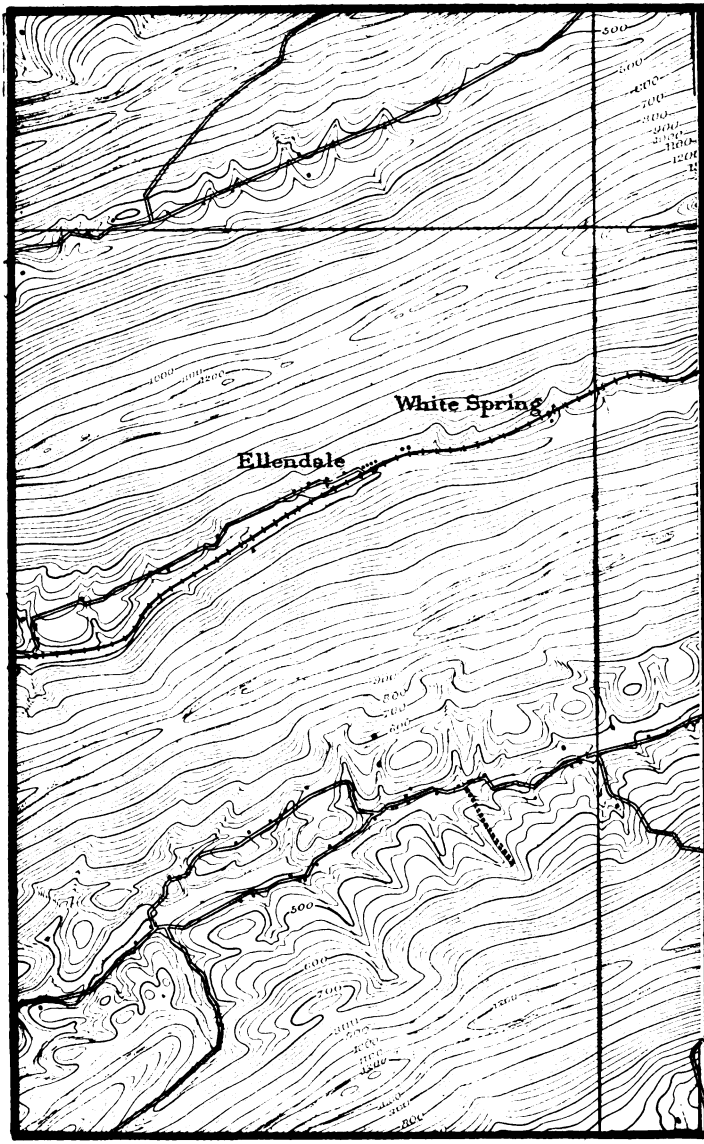

PLATE XVI. APPALACHIAN RIDGES. Contour interval, 20 feet. Scale, about 1 mile per inch. (Harrisburg, Penn., Sheet, *U. S. Geological Survey.*)

Mountains produced by vulcanism. — Many of the highest isolated mountains are volcanic cones (p. 46). Fujiyama, a volcanic mountain in Japan (Fig. 294), has an elevation above sea level of 12,365 feet. Many volcanic piles surpass Fujiyama in height, but few, if any, in symmetry of form. Aconcagua, an Andean cone on the border of Chile and Argentina, reaches 22,860 feet.

Many mountains have been formed also by massive intrusions of lava which have domed or lifted the overlying strata high above the level of the surrounding country

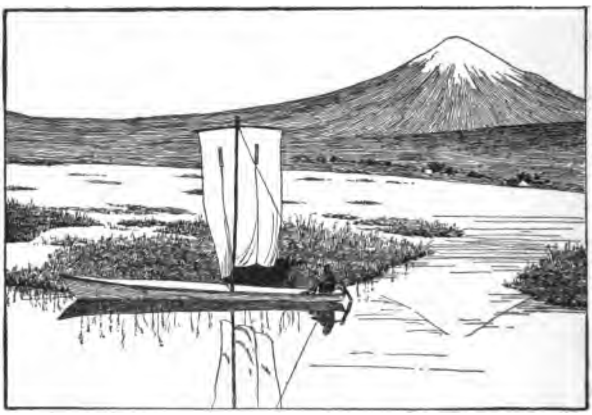

Fig. 294. — Cone of Fujiyama, Japan.

(p. 51). Frequently the cover of sedimentary rocks has been removed partially by erosion, exposing the central core of igneous rocks, from which the sedimentary beds often dip more or less uniformly in all directions. The harder sedimentary layers, wearing down less rapidly than the softer ones, may stand out as rudely circular ridges alternating with race-track shaped valleys, all of which inclose the igneous center. The Henry Mountains of Utah (p. 50), the Bear Paws and Little Snowies of Montana, and the Elk and Park ranges of Colorado are examples of this general class of mountains.

Certain mountains with the general structure of laccoliths — for example, the Adirondack Mountains — are not due directly to the intrusion and doming effect of their igneous cores. The original mountains formed by the intrusions were worn away in former cycles of erosion. The present mountains are residuals of strong rocks left standing by the removal of the surrounding weaker rocks.

FIG. 295. — A peak in the Wasatch Mountains, with large accumulations of talus about its base. (R. T. Chamberlin.)

Mountains of unequal erosion. — As already indicated, many mountains owe their existence simply to the superior resistance of their rocks, which have remained in bold relief after the removal of the surrounding softer rocks, or to a favorable position among drainage lines. Such mountains are sometimes called mountains of *circumerosion* or *circumdenudation*. Most mountain peaks (aside from volcanic peaks) are of this origin (Fig. 295). Pikes Peak, Colorado, and Mt. Mitchell, North Carolina, the highest peak in the Appalachian Mountains, are notable examples. The Catskill Mountains of southeastern New York are really a dissected plateau. Any maturely dissected plateau of considerable relief might similarly be called a group of mountains (Fig. 296).

Combination mountains. — Folding and faulting, vulcanism and unequal erosion, may all be concerned in the formation of lofty mountains. Many mountainous regions, furthermore, have had several periods of growth, between

FIG. 296. — Summits of Endicott Mountains, Alaska. Shows dissected plateau feature. (Brooks, *U.S. Geol. Surv.*)

which the upraised beds were much wasted by erosion (Fig. 297).

The destruction of mountains. — Unless renewed by diastrophism or vulcanism, all mountains are in time destroyed by erosion. It is to be noted, too, that the erosion of mountains commences as soon as they begin to rise, and continues throughout the long period of their growth, as well as afterwards. Accordingly, no mountain due to vulcanism or

FIG. 297. — Diagram showing structure of the beds in the region of the Santa Lucia Range, Cal. (From San Luis, Cal., Geologic Folio, *U.S. Geol. Surv.*)

diastrophism ever had the full height which those processes would have given it, if unopposed by erosion. As already pointed out, many mountains have been several times nearly or wholly reduced and revived again. The length of the life of a mountain which has ceased to grow is determined largely by its height, by the resistance of its rocks, and by the character of the climate. Where mountain slopes are steep, as is likely to be the case, erosion is rapid, and the products

FIG. 298. — Summit of Mt. Whitney, Cal. (Fairbanks.)

of weathering are removed promptly. The higher slopes of many mountains are accordingly of bare rock (Fig. 298). Daily changes in the temperature of the rocks are greater in the high altitudes of lofty mountains than in lower situations. Rock splitting is therefore important, and where the slopes are not too steep, mountains may be covered with loose, angular fragments broken from the rocks beneath (Figs. 299 and 95). Mountains receive greater rainfall than plains, and even in arid regions their steep valleys may contain rushing torrents. Rapid cutting is sometimes opposed, however, by the fact that the streams are clear (Why?). The absence of protecting vegetation on many upper mountain slopes is important (How?). Wind velocities are often great about mountain heights, but generally

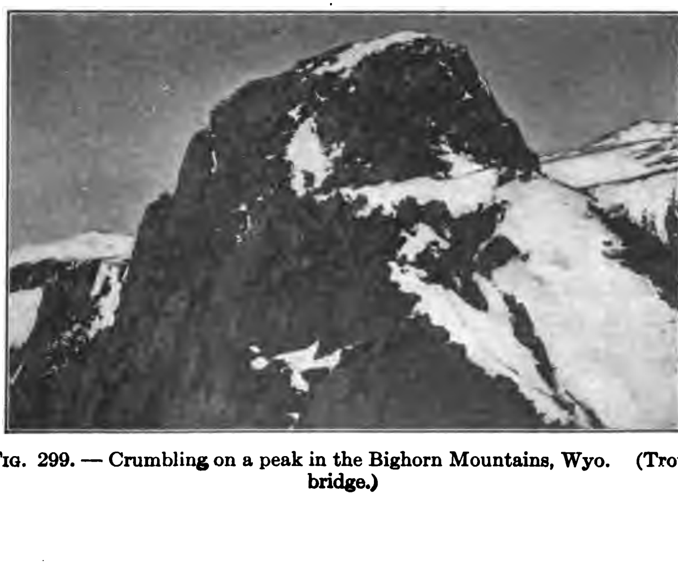

FIG. 299. — Crumbling on a peak in the Bighorn Mountains, Wyo. (Trowbridge.)

wind work is hindered through lack of suitable tools. Many lofty mountains are being reduced, also, by glaciers. In many other mountains with few or no glaciers at present, the striking results of the work of former glaciers may be seen (p. 219). In many cases neighboring glaciers drove their valley sides and cirques back into the mountain mass until they were separated only by sharp crests and narrow ridges (Fig. 300). Mountain scenery is due far more to the agents of land sculpture than to the forces of diastrophism.

Fig. 300. — Serrate mountain peaks due to erosion by valley glaciers. (Trowbridge.)

The subdued and gentle slopes of the later life of a mountain are worn less rapidly than the steeper slopes of its earlier career, so that its old age is likely to be longer than its youth and maturity combined. All lofty mountains are comparatively young, geologically speaking; if old, they would have been worn low. While very old mountains are low, obviously not all low mountains are old.

Plateaus

A plateau is a relatively elevated area of comparatively flat land, which is commonly limited on at least one side by an abrupt descent to lower land. While plateaus are usually

higher than plains, they may be lower. Though the ideal plateau has a level surface, many are deeply trenched by valleys and surmounted by ranges of high hills or mountains.

Distribution. — Extensive plateaus are confined largely to three classes of situations. (1) They may intervene between a lower plain on one side, and higher mountains on the other. The Piedmont Plateau, separating the Atlantic Coastal Plain from the Appalachian Mountains, is an example. (2) They may be surrounded more or less completely by mountains, as in the case of the vast plateaus of Central Asia and the Great Basin of western United States. (3) In some cases they rise abruptly from the sea, or from narrow coastal plains. The Iberian Peninsula and southern India are plateaus of this type.

Origin of plateaus. — Plateaus may originate in various ways. They may be built by successive lava flows, like the Columbian Plateau of the Northwest and the Deccan Plateau of India. The adjacent country may have been worn low or warped down, leaving a table-land. Or, the plateau may have been warped or faulted above its surroundings.

The erosion of plateaus. — Like mountains, all plateaus will be worn down to lowlands if not renewed. Mature plateaus are table-lands completely dissected by streams; the original flattish surface has been carved into hills and valleys, and slope and relief are at a maximum. It is at this stage that the arrangement of strong and weak rocks expresses itself most completely in the details of the topography. Such regions have so largely lost their plateau character, that, as in the case of the Catskills (p. 281), they are sometimes called mountains. In one sense there are no old plateaus, for, when worn low, they constitute plains.

Plains

Tracts of comparatively level and low land are plains. The term is used loosely, however, for there are hilly and

rolling plains as well as level ones, and high plains (Fig. 301) as well as low ones. Great plains are commonly terminated upon one or more sides by an abrupt ascent to table-lands or mountains.

Origin and classes of plains. — Various types of plains have been discussed in previous pages. Rivers make flood plains (p. 176), delta plains (p. 185), and peneplains (p. 147). The ancient ice sheets covered the more or less rough preglacial topography of extensive areas of northern United

FIG. 301. — A typical view on the high plains of western Kansas. (Gilbert, *U.S. Geol. Surv.*)

States with drift, forming drift plains (p. 451). The floors of extinct lakes form many flat lake plains, especially in glaciated regions (p. 453). Most lake plains are small.

Great plains, like the Atlantic and Gulf coastal plains of the United States and the vast interior plain which stretches from the Appalachians to the Rockies (Figs. 43 and 44, pp. 62 and 63), cannot usually be put in any of the above classes. Rather, they commonly contain many smaller plains of several or all of the types enumerated. In general, extensive coastal plains are former marginal sea bottoms, exposed either by elevation of the land or by lowering of the surface of the sea. Coastal plains may also be peneplains, or the

result of the filling of a shallow sea border by wash from the land. Great interior plains are either areas once high but now worn low, or, oftener, they are former coastal plains now separated from the sea by newer land.

The surfaces of plains due to recent emergence are likely to correspond approximately with the bedding planes of the strata, and the rocks are usually poorly consolidated (p. 37). The surfaces of peneplains developed on stratified rocks, on the other hand, bevel the edges of beds without regard to the dip, and the rocks below the mantle rock are generally well consolidated.

The changes produced on plains by erosion have been discussed sufficiently in earlier chapters.

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A number of the references under other headings, especially "The Work of Streams" and "The Composition of the Earth," are serviceable also here.

PART II

HISTORICAL GEOLOGY

CHAPTER IX

HISTORY OF THE EARTH

Geologic and human history compared. — By the word *history* we usually understand the story of men, nations, or civilizations. In reality this is only one kind of history, only a phase of a much larger history, which deals not only with the human race, but with all other animals, with plants, and with the earth itself back to the time of its beginning. The history of the earth and its inhabitants represents a vastly greater length of time than human annals, but much less is known about it. It is impossible to say just how long the earth has existed; but if we measure the existence of the human race in thousands of years, the duration of the earth must be reckoned at least by tens or hundreds of millions of years. While such enormous figures are quite too vast for comprehension, we may gain some idea of the length of time involved when we learn that although the great mountain ranges of to-day have remained almost unchanged since the dawn of human history, others like them have been built up and then entirely worn away, time after time, even during the later portions of geologic history. The stupendous cañon of the Colorado River in Arizona seems to our eyes one of the fixed and everlasting features of the earth; yet it has all been made in a very recent period of the earth's existence.

How geologic history is worked out. — The threads of human history have been gradually pieced together from

written records, old monuments and ruins, legends, and such things. Of geologic events there is almost no written record. We must depend upon (1) the testimony of facts afforded by the study of the rocks, and (2) our ability to interpret them according to the natural laws which control everything that happens in the universe.

Record of physical changes in the earth. — When carefully studied, the rocks may be made to tell much about their own history. Take, for example, the conditions represented in the diagram (Fig. 302). It is evident that the lower rocks have been folded, whereas the upper layers have not. Mountains were doubtless formed by the folding, but the unconformity shows that they were worn away, leaving a nearly flat surface upon which the sand, which was to become the sandstone, was laid down. The sandstone is evenly stratified, as if the sand had been assorted by currents of water; and if the shells of marine animals are found embedded in the sand, they indicate that the sand was spread out on the bottom of the sea. If the sandstone is now hundreds of feet above the sea and many miles inland, as is true in many cases, it indicates that notable changes have taken place in the distribution of land and sea and in the height of the land above the sea. From a single section of rock it may thus be possible to learn much that has happened in its vicinity in the ages long past. From many such fragmentary records as this, a fairly continuous story of changes of land and sea, mountain growths, base leveling, and other events has been worked out, especially for the latter part of the earth's history.

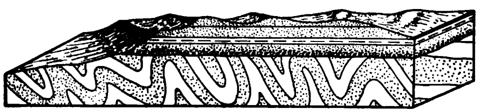

FIG. 302. — Ideal section of sedimentary rocks.

Record of changes in living things. — On first thought the different kinds of animals and plants about us seem as changeless as the hills and continents. Each bird and each tree, for example, produces young almost exactly like itself, so that the

kind seems to be permanent. Yet we know that by skillful manipulation a new variety of fruit tree or a new breed of poultry may be produced from the original familiar forms. Such changes have been going on under natural conditions through all the ages since life began, though more slowly; and these changes, like the slow wear of the rivers and waves, have brought about great transformations.

If we examine the most recently formed strata of mud and sand, we may find in them the shells of oysters, corals, and other water-inhabiting animals hardly to be distinguished from those which live in the ocean today. But in much older rocks the shells we might discover would bear only a faint resemblance to the existing species. All of the species of animals which lived when those sediments were being deposited may have long since become extinct and have been replaced by newer types more like those of the present. The shells and other traces of animals and plants preserved in the rocks are called *fossils;* and, as we shall see, fossils are of great importance because they enable us to trace the progress of life from one stage of its existence to another. When geologists first discovered that in a given series of strata the fossils in the lower layers were distinctly different from those in the upper, they supposed that the earlier animals had been destroyed by some great catastrophe, and that a new set had then been created to replace them. Soon, however, it became clear that the animals in the upper beds were distinctly related to those in the lower, and that the differences between them are chiefly matters of degree. The belief thus became established that the modern animals and plants have descended from older and older species by a series of very slow changes occupying millions of years.

Each individual animal and plant to-day begins its existence as a single minute cell, which, as it grows, divides and subdivides many times until it produces the many cells which the adult body contains. There is every reason to believe that, like the individual animal, the whole animal kingdom has

grown from very simple types, which were but single microscopic cells of living substance.

Groups of Animals and Plants[1]

The common forms of plants and animals. — Every one recognizes in a general way the difference between live things and inanimate objects, and it is not difficult to perceive certain fundamental traits which distinguish the one from the other. We say the tree is alive because it grows by taking into itself new substance, produces seed which makes new trees, and finally dies. Granite cannot grow, in the same sense, nor can it produce other granites; it is not alive. Similarly, among living things themselves, we can usually distinguish at sight plants from animals, birds from fishes, mosses from grasses, etc., but often without being able to tell just what the differences are. The following descriptive outline will help to make plain the distinctions between the familiar groups of living things and will also impart some acquaintance with others which are now rare or extinct, and hence are unknown from everyday observation.[2]

Plants. — Plants assimilate food, grow, and reproduce their kind; but most of them do not seem to feel, nor can they move about at will. They have the ability to use as food, not only water, but carbon dioxide from the air and certain materials dissolved in the water. The vast majority of them are green in color. There is scarcely any single feature, however, which will serve to distinguish all plants from animals.

[1] The following summary of the more important groups of living things is inserted here to aid the large number of students of geology who have little or no acquaintance with biologic science. It is necessarily very brief. For additional information reference may be made to any of the more recent textbooks of zoölogy and botany, or to the Zittel-Eastman Textbook of Paleontology.

[2] Where possible the common English names for the different groups have been used, but inasmuch as some of the divisions have only scientific names, usually of Latin or Greek origin, it has been necessary to make use of them.

(1) ALGÆ, FUNGI, BACTERIA, ETC. (Thállophytes).

The simplest of all plants. Among them are seaweeds, diatoms, molds, yeast, mushrooms, etc. They have no distinct roots or leaves, and they are reproduced, not by seeds, but by minute germs or *spores*. Some merely divide, each part then becoming a distinct plant. The majority of thallophytes live in the water or in very moist places, and some are mere single cells of jellylike substance, too small to be seen with the naked eye. The fungi, bacteria, and many others are not green in color.

(2) MOSS GROUP (Brýophytes).

More advanced plants than the last, in that some of them have definite leaves and stems. But true seeds and flowers are still lacking. They include the mosses and liverworts, — all small, delicate plants.

(3) FERN GROUP (Pterídophytes).

In the ferns and their allies for the first time we find a system of tubes and pores which allow the circulation of sap and air within the plant. Some ferns are treelike and have woody tissues, but most of them are small herbs. Geologically the chief interest now centers in a group which we may call the *seed ferns* (Pteridospermæ),[1] — all of them now extinct. These had all the appearance of true ferns, and were formerly regarded as such; but it is now known that they possessed fruitlike organs with true seeds, which indicate a close relationship with the next group. They seem to be intermediate in many respects between ferns and cycads.

[1] The older classifications of plants have recently been modified in consequence of the studies of Seward, Scott, and others on fossil plants. The scheme here used is adapted partly from Scott's writings.

(4) SEED PLANTS (Spermátophytes).

This group, distinguished from all except the transitional seed ferns by the production of true seeds, contains all the higher plants which we ordinarily observe, as well as many which are extinct. It is divided into two important sections: —

(a) *Naked-seed section* (*Gýmnosperms*).

The seeds are naked and there are no flowers, in the common sense of that word. Here belong the pines and other "evergreens," as well as the *cycads*, — palmlike plants now of small importance, but formerly very abundant (Fig. 422).

(b) *Incased-seed section* (*Ángiosperms*).

Seeds incased in a husk or shell. This section includes the majority of our familiar trees and shrubs, such as oak, elm, apple, palm, rose, etc., and the grasses, grains, and many herbs. To-day it is the most important group of plants, but it was the last to appear, and in the older geologic periods no such types existed.

Animals. — Animals differ so markedly from plants that all but the simplest forms may readily be recognized as being distinct. They have the power of making voluntary movements, they have the sense of feeling, and they depend for food on the bodies of plants or other animals. The higher animals also possess the faculties of seeing, hearing, etc., and even of intelligence, characteristics which separate them more and more widely from plants.

(1) PROTOZOANS.

The simplest animals are so much like the simplest plants that only a few things, such as the power of motion and evident sensation, distinguish them. Even these tests fail in the lowest forms. Most

of them are minute beings which live in water. The jellylike *amœba* (Fig. 303), consisting of a single

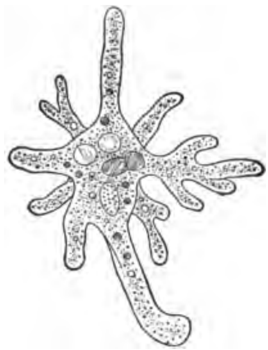

FIG. 303. — The Amœba, a protozoan without a shell.

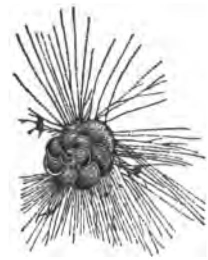

FIG. 304. — A protozoan with calcareous shell and delicate threads of protoplasm (Globigerina).

cell, is an example. The protozoans have no distinct organs, — not even a stomach. Some are incased in tiny chambered shells, which may be preserved as fossils (Fig. 304). These shells often make a large contribution to the formation of limestones.

(2) SPONGES.

They are composed of many cells but still lack well-defined organs. They are provided with countless pores and tubes through which water circulates freely and feeds each individual cell. They have no shells, but most of them contain little hard rods and spines (*spicules*) embedded in the flesh (Fig. 305), and usually joined into a solid framework. These spicules are often found preserved in the rocks.

FIG. 305. — A simple sponge, opened to show the sacklike form, and with the skin removed to show the tack-shaped spicules which form its skeleton. (After Haeckel.)

(3) Polyps (Cœlénterates).

Animals having a central cavity which serves as a stomach, and a series of radiating arms or tentacles around the mouth. They are all aquatic and most of them live in colonies attached to each other. Many resemble plants in their general appearance and stationary habits of life. The classification of this group is complicated, but the following divisions are of special interest.

(a) *Jellyfish* (*Medusæ*).

Floating jellylike animals (Fig. 306) of great beauty and interest, but devoid of hard parts and therefore rarely preserved as fossils.

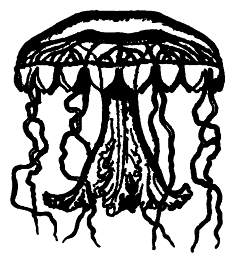

Fig. 306.—A modern jellyfish or medusa.

(b) *Hydroids*.

Delicate plantlike animals, most of them without hard parts. Only the extinct group known as the *graptolites* are common in the fossil state. They were minute polyps attached in rows to long stems; in appearance the fossils resemble serrate blades of grass (Figs. 346 and 347).

(c) *Corals*.

Most of these polyps are provided with a limy shell, exuded by the outer side of the body, and are therefore readily fossilized. In some species each animal lives by itself and leaves a horn-shaped skeleton (Fig. 348), but the majority are attached to each other in the form of compact or branching colonies (Figs. 349 and 372). The young corals swim freely in the water, but become fixed to the sea bottom before they reach maturity.

(4) ECHÍNODERMS.

Under this name are included such animals of the sea as starfish, sea urchins, and crinoids. They possess distinct nerves, digestive organs, and a circulatory system, in which the fluid is water instead of blood. These features mark a notable advance over the polyps. Most echinoderms are protected by a hard shell composed of a mosaic of little plates.

(a) *Crinoids.*

Often called *sea lilies*, because they are attached to the sea floor by stalks, while the upturned mouth is surrounded by long, feathery arms (Fig. 364). *Cystids* and *blastoids* (Fig. 390) are related forms.

(b) *Starfish* (including the brittle stars).

On account of their star-like shape, these animals will not be confused with any others.

FIG. 307. — A modern sea urchin with the spines attached.

(c) *Sea urchins* (*Échinoids*).

Round or egg-shaped forms which in life are covered with spines (Figs. 307 and 444). They are very abundant to-day along the seashores, but are less important among fossils.

(5) WORMS.

A large group of animals which are still more complex in structure than the echinoderms. As they are soft-bodied they are not commonly preserved in the rocks, but their burrows in the sand are often found as tubes in sandstone.

(6) Lamp Shells (Brachiopods).

These animals are now rare and are not well known even by their English name. They are inclosed in a pair of shells (Figs. 369 and 396), and hence are easily confused with the lowest group of mollusks; they may be distinguished from the latter by the bilateral symmetry of their shells. A pair of spiral armlike organs aids in getting food to the mouth. In the earlier forms these spirals were soft and hence were not fossilized. Later, some of them came to have solid supports of lime carbonate which were durable (Fig. 308). Fossil brachiopods are varied in shape and are abundant in many of the older rocks.

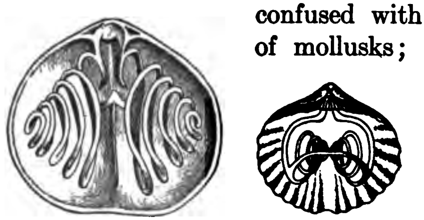

Fig. 308.—Internal structure of the shells of brachiopods.

(7) Mollusks.

In this group are found not only well-developed internal organs, but, in the higher types, even a distinct head, eyes, and teeth. All are soft-bodied, but they are usually protected by a hard, limy shell.

(a) *Bivalves* (*Pelécypods*).

Forms like the common oyster and clam, provided with two shells, usually nearly alike, which hinge together on one side (Figs. 352 and 374).

(b) *Snail group* (*Gástropods*).

The snail and its relatives have a single conical shell which is almost always twisted or coiled into a spiral form. The earliest and most primitive types are merely cap-shaped (Fig. 336), but later species developed a great variety of coiled shells

(Figs. 350, 365, and 443). The snail-like mollusks live on land, in fresh water, and in the sea.

(c) *Chambered mollusks* (*Céphalopods*).

The cephalopods take rank as the highest of all the mollusks. They have well-developed eyes, and many are active, voracious animals.

i. Nautilus division.

The animals of this division are now rare, although many existed in earlier periods. The shell is a long tube divided into chambers by a series of cross partitions (Fig. 353). A small tube or *siphuncle* extends back through all the chambers to the apex of the shell. The earlier shells were straight, but soon there appeared curved (Fig. 354) and coiled forms (Fig. 355). Spiral shells, however, are rare. Later in the history of the cephalopods the partitions became more or less folded into convolutions (Fig. 391), which are shown on the inner surface of the shell by angles and loops in the lines (*sutures*) formed by the junction of the partition with the shell. Eventually this folding of the sutures became extremely complicated (Fig. 447).

ii. Cuttlefish division.

The cuttlefish, octopus, and squid, although common enough to-day, have left fewer fossils than the last group. Their stout bodies, with long, fleshy tentacles surrounding the head, have no hard parts, except that some had a cigar-shaped shell embedded in the body of the animal (Fig. 429).

(8) ARTHROPODS ("Jointed-leg" animals).

Besides less familiar types, this group includes the insects, spiders, centipedes, and crayfish, — that is to

say, all the invertebrates which are provided with jointed legs. They have well-developed organs of touch, sight, smell, etc., and their internal anatomy is highly complex.

(a) *Crustaceans.*

Animals, usually aquatic, the majority of which are covered by a hard outside shell made of a number of plates. Here belong the lobsters, shrimps, etc., of to-day, and the even more important group of *trilobites* which are now extinct. An idea of the general appearance and great variety of the trilobites may be gained from Figures 333, 334, 344, and 361.

(b) *Air-breathing arthropods.*

The insects, spiders, scorpions, and centipedes are common on the land surface to-day, but fossil remains of them are scarce. The animals of the land are apt to be left in positions where they are less likely to be preserved as fossils than are those which live in the water.

(9) VERTEBRATES.

The highest branch of the animals contains those which have a backbone or vertebral column. Among these are the fishes, frogs, reptiles, birds, and four-footed beasts in general. The subdivisions of this great group we usually recognize without difficulty.

(a) *Fishes.*

Fishes are the lowest of the more familiar vertebrates and are the only group which inhabits the water exclusively. They have poorly constructed skeletons which, in some species, consist chiefly of cartilage instead of bone. In brain power, also, they are the least advanced. They swim by means of fins and breathe water through gills.

(*b*) *Amphibians.*

This group, containing frogs, salamanders, etc., is intermediate between fishes and reptiles. As the name indicates, they live partly in water and partly in air. The young, called tadpoles if frogs, breathe with gills and are otherwise much like fishes; but before they are fully grown they usually develop lungs, shed their fins and gills, and change their habits accordingly. Some amphibians, however, never relinquish their aquatic habits.

(*c*) *Reptiles.*

The snakes, crocodiles, lizards, turtles, and still other forms now extinct, may at first glance seem to be like the amphibians, but in reality they are very different. They breathe air exclusively and their skeletons are usually rather solid and well constructed. They were formerly far more abundant and important in the world than they are now.

(*d*) *Birds.*

The feathered vertebrates are so plainly set off from all others as to need little description. In spite of the dissimilarity of the two groups, it is known that the birds are much more closely related to the reptiles than to any other class (p. 413).

(*e*) *Mammals.*

The common quadrupeds, such as cattle, bears, mice, bats, and kangaroos, which as a rule bring forth live young and nourish them with milk, are now the leaders of the organic world. Most of them are clothed with hair and inhabit the land, although some, like the whales, are bare and live in the water. As a group the mammals excel all other animals in intelligence and consequently in power, for in all the history of life, cunning, skill, and resourcefulness have been of more avail in the combat for existence than mere strength or size.

Fossils and their Uses

Preservation of fossils. — The traces of animals and plants preserved in the rocks, and known as *fossils,* are made in a variety of ways. In rare cases the entire animal is preserved, — as when insects are inclosed in resin which afterwards becomes *amber.* More frequently only the bones or shells are left. Often the shells have been dissolved out and other mineral matter substituted, giving us natural casts of the original. In still other instances we have only the markings made by the living animals, as the burrows of aquatic worms in the sand or the trails of clams in the mud. Whatever the nature of these vestiges of life they are all fossils.

Manifestly not all animals or plants are allowed to become fossils. The great majority are devoured, while others decay in the open air and disappear. Only those which are protected from the atmosphere are preserved. Complete decay is often prevented if the animal or plant becomes lodged in a bog or lake or beneath the sea. Since the sea is far more extensive than lakes or marshes, it is not surprising that the majority of fossils which have been found are those of marine animals. Correspondingly there is a scarcity of fossil remains of the animals and plants which lived upon the dry land.

Evidence of past conditions. — Since fossils tell us of the living things of bygone ages, obviously they are of interest to the biologist. In geology, however, they have additional uses apart from the study of life itself. For example, we may find in Iowa a bed of limestone which contains abundant fossil corals and other animals of the sea. From this we infer a variety of things about the conditions in the central part of the United States in that remote period when the limestone was formed. Evidently the sea then extended far into the interior of the continent. That its waters were shallow and relatively warm is shown by the presence of the kinds of corals which inhabit only the shallow portions of tropical seas. In

brief, we may learn from the fossils alone something about the geography and the climate of the remote past.

The succession of faunas. — Fossils also enable us to tell the relative age of rocks in different parts of the world; and herein lies perhaps their greatest value to geology. Since each successive bed of sediment is laid down upon some other which was there before it, it is obvious that, in any exposure of undisturbed rocks, the beds which lie below are older than those above. This rule sometimes fails to hold, as where rocks have been so highly folded that they have been actually bent back upon themselves, but such exceptions may with care be detected in the field. It is evident, therefore, that if we could find in the sides of some deep valley, like that of the Colorado River, a complete pile of the sedimentary strata which have been laid down upon the earth since the dawn of geologic history, we should have a complete *stone record* of sedimentation. But unfortunately no section even approaching this in completeness is known; we have only fragmentary exposures more or less concealed by soil, forests, and bodies of water. It is here that fossils come to our aid.

Figure 309 is drawn to represent two bare hills cut through to show the layers of which they are composed. In the hill on the left we find the remains of a certain *fauna* or society of animals *A* in the lowest stratum, a slightly different fauna *B* in the next higher stratum, and so on for each stratum. In studying a number of other outcrops in the same vicinity, we find that the same sequence of faunas prevails in all. We thus have a *standard section* for beds *A–E*. Now suppose that in the right-hand hill, we find, at the base, rocks which contain fauna *D*, and above that fauna *E*, while the higher layers afford new faunas unlike any seen in

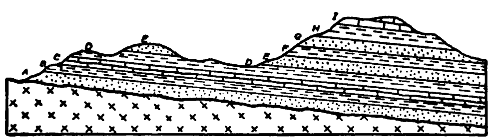

FIG. 309. — Section of strata containing fossils of different ages.

the first locality. The coincidence of the lower fossils with those of *D–E* of the earlier sections establishes our starting point, and if the beds are conformable, so that we know there was no interruption in deposition, we may now designate the upper faunas as *F*, *G*, *H*, and *I*. This process of matching and piecing out local sections has been carried on until we have a nearly complete series of sections extending from the present sediments back to rocks of very ancient times.

The time value of unconformities. — Thus far we have considered only conformable strata, those which were laid down one upon the other without interruption of any kind. It often happens that the section under study contains an unconformity. Without fossils this unconformity would tell us that the region had emerged from the water after the deposition of the lower beds, had been eroded, and again submerged before the upper layers were formed; but we should not know how much time had elapsed while it remained as land. Suppose, however, that the beds contain fossils, and that the fauna just below the unconformity is like *B* in our first section, while the one next above is identical with *G*. We then know that faunas *C–F* are lacking and that the region may have been land through all of the time which was required for the gradual evolution of fauna *B* into the new fauna *G*, or that it was land during let us say the *E* and *F* periods and that the deposits of the *C* and *D* periods were worn entirely away at that place.

The geologic column. — The completed series of sections, often called the *geologic column*, is useful as a standard to which we may refer any isolated rock formation in which we can find the necessary fossils. Furthermore, an examination of it showed very early that it contained certain natural divisions which could be recognized all over the world, and from time to time geologists have given to these divisions names which are in general use.

The dividing lines between the parts were usually the planes at which sudden and marked changes in the fossils were

found. For example, fossil reptiles were abundant in the rocks which represent a certain part of the geologic column (Mesozoic era), but above that section they are rare, while on the other hand the mammals appear in profusion. This point of change made a convenient place to separate one division from another. At first such changes in the fossils were made the sole basis for subdividing the column, but now we are coming to realize that these very transformations among the animals and plants are brought about by corresponding changes in the conditions under which they lived; or, in other words, by changes in the climate, the topography, the relations of land and sea, etc. So, we now try to divide the geologic record at the points where these revolutionary physical changes are indicated, and to make corresponding divisions of geologic time itself. Thus there are two kinds of divisions; one for the rocks themselves, and the other for the time represented by the rocks:—

Time Divisions		*Rock Divisions*
Era	—	Group
Period	—	System
Epoch	—	Series

There is some difference of usage among geologists as to how the geologic column should be divided, particularly as to the rank of certain of the divisions. The classification here adopted, although not to be regarded as permanent, agrees well with the facts now known. As the names of the divisions will be constantly used in later pages, the following table should be learned thoroughly.[1]

[1] The names of these time divisions have grown up in a somewhat haphazard way in the course of a century or more of progress in the study of geology. At an early time it was supposed that certain periods were distinguished by the formation of particular rocks, and so we have such names as "Cretaceous" for the period when the chalk (Latin *creta*) of England was produced. Later it has become customary to name periods after regions in which the rocks of that age are well known; thus Devonian is named for the county of Devon in England.

Table of Geologic Divisions

Era and group	Period and system
Cenozoic era and group	Quaternary period and system.
	Tertiary period and system.
Mesozoic era and group	Cretaceous period and system.
	Comanchean period and system.
	Jurassic period and system.
	Triassic period and system.
Paleozoic era and group	Permian period and system.
	Pennsylvanian period and system.
	Mississippian period and system.
	Devonian period and system.
	Silurian period and system.
	Ordovician period and system.
	Cambrian period and system.
Proterozoic era and group	Keweenawan [1] period and system.
	Animikean [1] period and system.
	Huronian [1] period and system.
Archæozoic era and group	Archæan period and system.

Periods older than the geologic record. — Back of these periods and eras there stretches a vast lapse of time of which we know so little that the use of definite time divisions is hardly justified as yet. It includes the beginning of the earth and its development through a series of exceedingly slow changes.

Imperfect record of the earth's history. — If we had as complete a knowledge of the earth in its earlier periods as we have of its present state, we should be able to construct a fairly complete history of it. That would include the changes which have occurred in the shapes of seas and land, in the mountains, plains, and other topographic features, in the distribution of volcanic districts, the development of the many groups of animals and plants, the fluctuations of climate, and many other important things. As it is, only a part of these facts have been recorded in the rocks; only a small portion

[1] These names are applied only in the Lake Superior region of the United States. The rocks which represent the oldest periods are almost devoid of fossils, and it is therefore hardly possible to extend the same names to other regions, as has been done in the case of later periods.

of the record itself is now exposed and accessible; and much of that portion still awaits investigation. It is clear, then, that the story of the earth can be little more than outlined, as yet, and that it grows more obscure as we trace it back into the remote past.

Questions

1. What is suggested by the finding of sea shells in a series of horizontal beds on top of a mountain 3000 feet high, as in Figure 310?

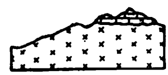

Fig. 310.

2. What changes may be inferred from the sections of sedimentary rocks represented in Figures 311, 312, and 313?

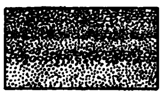

Fig. 311.—Sandstone and conglomerate.

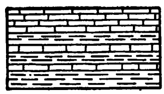

Fig. 312.—Limestone and shale.

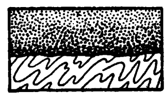

Fig. 313.—Conglomerate and sandstone resting on folded schist.

3. As between the fishes and the mammals, which would you expect to find preserved in the older rocks? Why?
4. What would be indicated by finding a comparatively recent group of fossils in beds lying beneath rocks which contained much older types?
5. What kinds of fossils would you expect to find in sediments deposited in river valleys, as against those laid down in the open sea?
6. In what kind of volcanic rocks might fossils be found? Why not in the others?

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CHAPTER X

ORIGIN AND DEVELOPMENT OF THE EARTH

The earth and the planets. — It is a matter of common knowledge that the earth is a ball which revolves about the sun, — another but much larger body of similar shape. Seven other planets more or less like the earth also wheel about the central sun (Fig. 314). Among them are the familiar stars, Jupiter and Venus. Four of the planets are larger than the earth, three are smaller. Two are nearer the sun, while five are farther away from it. The moon is a much

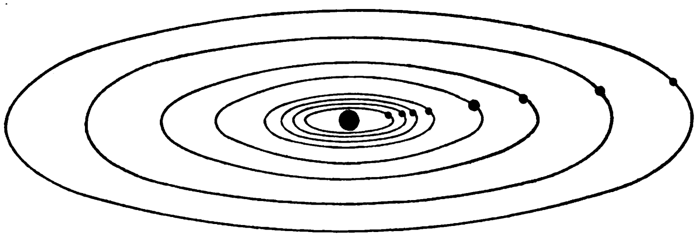

FIG. 314. — Diagram of the solar system. The size of the sun and particularly the planets is enormously exaggerated as compared to the breadth of the orbits.

smaller body, which is controlled by the gravity of the earth and therefore revolves about it. Most of the other planets have similar moons (satellites), — Saturn has nine of them. In addition to its motion around the sun, each of the planets rotates on its own axis, much as a top spins while gliding about on the floor. It is a significant fact that all of the planets move in the same general direction, and the nearly circular paths which they follow, year after year, lie so nearly in the same plane that the whole system may be compared in shape to a disk. As we now know it, this ***solar system***

is a beautifully adjusted and harmonious family of planets which we may be sure has not been seriously disturbed during many millions of years in the past.

Theories of Origin

The heavenly bodies have always interested men to such a degree that many attempts have been made to explain their origin and arrangement. Up to the sixteenth century it was believed that the earth was the central and largest part of the universe, and that the sun, moon, and stars moved about it. Men were very generally of the opinion that these bodies were created in their present state and were maintained for the express purpose of giving light to the human inhabitants of the earth. It was only after Copernicus, in the sixteenth century, showed that the earth is merely a small member of a great system, that this narrow and egotistical view began to give way to a broader conception of the heavens.

The nebular theory of Laplace. — Near the end of the eighteenth century the distinguished French mathematician Laplace worked out a most ingenious theory which seemed for a time to account for nearly every peculiarity of the solar system. He suggested that it was originally derived from a huge spheroidal mass of gas, which was so hot that even the metals and the materials which form the rocks of to-day were then expanded into an incandescent vapor many times thinner than air. As this *nebula* gradually cooled, it shrank, and its shrinkage made it rotate faster upon its axis. The faster it whirled the stronger became the centrifugal force on the outside of the spheroid. This tendency of things to fly off into space was at first counteracted by the attraction of gravity within; but eventually it became equal to gravity on the equator of the spheroid and the material there then ceased to contract.

The equatorial portion was then left as a ring encircling the ever shrinking remainder. This ring is supposed to have

condensed into a ball, which became the outermost planet (Neptune). Other rings were produced one by one in the same way, until all the planets had come into existence, and the remainder of the original mass was left as the sun. The satellites of the planets were thought to have originated from equatorial rings left behind by the contracting planets before they solidified. On this theory, then, the earth began as a globe of intensely hot vapor which cooled down to a liquid, and finally crusted over with a solid shell of rock, while the interior remained in the molten state. At that stage the surface of the earth was so hot that water could exist on it only in the form of vapor. The atmosphere was then, according to the theory, very heavy, hot, and utterly unfit for living things. In time it cooled sufficiently to allow the water vapor to condense and fall as rain. For a long time the surface was still so hot as to boil off the water as it fell. This process gradually cooled the surface, however, and finally its temperature was sufficiently low so that the falling rain remained as surface water. Then the oceans began, and as the temperature of the water was reduced and the atmosphere became somewhat freed from carbon dioxide and other unwholesome gases, the surface of the globe became fit for living things.

For a century or more Laplace's theory seemed to fit the facts then known, and it was regarded as essentially true. But we must remember that, from the very nature of the problem, it is unlikely that any theory of the earth's origin can be proved. The more critical studies of recent years have shown that the Laplacian hypothesis presents many serious difficulties. Efforts have been made to meet these by various changes in the details of the theory, but the more serious objections were not removed by any of these modifications, and doubt arose even as to the fundamental ideas of the hypothesis. For example, it now seems improbable that the materials which became the planets could have separated from the equatorial portion of the nebula in the

form of rings; and many other difficulties of an even more fundamental nature have been pointed out. A new theory, which seems to explain the facts we now have at command better than did the older hypotheses, has recently been worked out on a quite different basis. It is known as the *Planetesimal theory*.[1]

The planetesimal theory. — Many more nebulæ are known now than were known when Laplace advanced his theory. But among them all none have been found which have a central mass surrounded by a ring. On the other hand, researches show that the great majority of nebulæ are spiral in form (Figs. 315 and 316). Such a nebula consists of a luminous center with spiral arms or streamers issuing from opposite sides. On these arms there are knotlike condensations at various points. The spiral form suggests that the whole mass has a whirling motion about the center. It is thought that the thinner portions of these nebulæ are composed of scattered particles of various sizes, while in the knots the particles are less scattered. All of the particles, including those of the knots, are believed to be revolving, each in its own independent orbit, about the central mass, much as the earth revolves about the sun. Since these bodies behave like tiny planets, they are called *planetesimals*. The suggestion is made that our solar system may have grown from such a nebula. It is conceived that the knotlike bodies in the arms became the centers of growth for the planets, gradually gathering in the planetesimals about them. Some of the "shooting stars" or meteorites that enter our atmosphere are probably but planetesimals still being gathered in, — a suggestion that the growth of the earth is still continuing, although with exceeding slowness.

On the new hypothesis, then, the earth grew from a nebular knot to its present size by the slow ingathering of the smaller particles or planetesimals. In the earlier stages of its existence

[1] The work of Professor T. C. Chamberlin of the University of Chicago, assisted on the mathematical side by Dr. F. R. Moulton.

as a planet, it may have had no atmosphere. If that was true, the great processes of erosion could not then have been in operation, since they are largely dependent upon the presence of an atmosphere.

FIG. 315.—Spiral nebula. (Photograph by Ritchey at the *Yerkes Observatory*.)

Gases, and therefore air, have a marked tendency to expand and diffuse themselves through space. It is known that the earth is able to keep its atmosphere only because of its strong gravity, and that a few gases, notably free hydrogen, are too active to be held by it. Since in small bodies gravity is much

weaker than in large ones, it is clear that small bodies are less likely to hold an atmosphere than large ones. Thus the moon seems to be quite devoid of an atmosphere to-day. If the earth had gravity enough to hold an atmosphere at the outset,

FIG. 316.—Spiral nebula. (Photograph by Ritchey at the *Yerkes Observatory.*)

it probably had one. If its gravity was not sufficient at first, it eventually became so, as the earth grew; and so the planet slowly acquired an atmosphere and, later, oceans. The method by which the atmospheric gases were supplied is simple, and doubtless continued in a measure down to the

present day. The overpowering force of gravity tends to compress the material of the earth into an ever denser form, and this compression generates heat. As the planet grew larger, its gravity increased in strength. The interior was therefore more compressed and became constantly hotter. All rocks, whether such as belong to the interior of the earth, or such as come down as meteorites, contain a variety of gases or material out of which gases may be formed by heat. The growing pressure and heat of the earth's interior are therefore supposed gradually to have driven out some of these gases, and thus furnished the material for an atmosphere. The gases issuing from volcanoes to-day illustrate this process. So, also, particles of gas are supposed to have been parts of the nebula and to have been gathered in from the outside. It was therefore only necessary for the earth to acquire sufficient force of gravity to hold these gases upon its surface, to enable it to accumulate an atmosphere. At first this probably consisted of such gases as carbon dioxide, nitrogen, and water vapor, as these are the ones chiefly given off by rocks and meteorites. Carbon dioxide, however, is chemically active and must have been partly disposed of by uniting with the rocks, while nitrogen is little disposed to enter into combination and must have constantly accumulated. At the same time certain agencies that decompose water vapor probably gave rise to oxygen.

As the water vapor accumulated it eventually condensed into rain, and with the rain came the beginning of other geological processes. At first, the water circulating through the porous outer portion of the earth dissolved out minerals in certain places and deposited them elsewhere in the form of cementing material and vein fillings. Later, as the ground water level rose, ponds and lakes appeared in the lowest depressions of the earth's surface, for the haphazard infall of the solid planetesimals probably left many irregularities, and in addition there were numerous volcanic craters. As time went on these lakes grew and coalesced into great seas and

oceans, and thus the hydrosphere became fully developed. At the same time the erosion of the uplands commenced and sediments began to accumulate in the depressions.

With the establishment of these great processes, suitable heat, light, moisture, air, and all the other conditions which seem necessary for the existence of life were present, and life probably began. But the origin of the first living things is still among the unsolved problems of science. There is, however, every reason to believe that, whatever their origin, the earliest forms of life were very simple, and probably more like the lowest plants of to-day than like animals. From these early forms all later kinds are thought to have been derived by a vast number of slow changes, probably occupying many tens of millions of years.

Volcanoes probably appeared on the earth at a comparatively early stage in its history, long before it had grown to the size of the moon. There is reason to believe that volcanic action gradually increased in prominence and reached its climax after the earth had attained its present size.

The two theories compared. — In many respects these two theories of the earth's origin are directly opposed to each other. Under the Laplacian view the planet was at first larger and hotter than now, and it continually cooled and contracted until it became partly or entirely solid. Under the planetesimal theory the earth grew larger by gathering in material from outside, and it was not necessarily ever hotter than now, if as hot. Under the first, the atmosphere has become thinner and poorer, from the time when it was exceedingly heavy, dense, and composed largely of steam; under the second it has grown larger and richer in material, and it was never hot. According to the Laplacian theory the oldest rocks which we might hope to find would be entirely igneous, — portions of the original crust which coated the surface of the molten globe; but under the later hypothesis, we should expect not only the igneous materials derived from volcanic eruptions, but sedimentary deposits as well, in the

very oldest rocks we could hope to reach. For still another contrast, we may turn to the future fate of the earth as forecast by each of the opposing theories. If we follow the older conception, we must predict a gradual cooling and final refrigeration of the earth and even the sun, the absorption of its dwindling atmosphere within itself, and the death of all living creatures. Under the newer hypothesis, the outlook is less gloomy. Looking ahead as far as imagination will safely carry us, we can see no prospect of destructive changes. The infinitesimally slow growth of the earth and its atmospheric envelope should continue, and the evolution of living things into higher and better kinds should have ample time for accomplishment.

Questions

1. What prevents the planets from leaving the sun?
2. If Jupiter should pass close to the earth, what would happen to the moon? Why?
3. If the Laplacian theory is correct, what materials should have formed the first solid part of the earth? In what order should other materials have been added?
4. If the planetesimal theory is correct, which would be brought into operation first, weathering or wave action?
5. On the same hypothesis would the waters of the first seas have been fresher or salter than in existing oceans? Under the Laplacian hypothesis?
6. On the Laplacian theory how should the volcanic activity of early times compare with that of the present?
7. One of the satellites of Mars revolves about the planet much faster than Mars turns on its axis. How does this fact bear on the Laplacian theory?

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CHAPTER XI

THE ARCHÆOZOIC ERA

The oldest rocks. — The most ancient part of the earth's history of which we have any tangible record in the rocks is quite as shadowy and obscure as the dim legendary period of human annals. The record has been in large measure destroyed, and that which remains is confused and difficult to interpret. The rocks which were made during the Archæozoic era are the oldest of which we have any knowledge. They compose what is called the *Archæan system*. This underlies all later systems of rocks, and over most of the globe it is still buried beneath thick layers of younger rocks (Fig. 317). In most places where Archæan rocks can now be

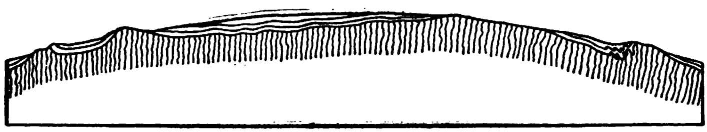

FIG. 317. — Ideal cross section of North America, showing how the Archæan rocks underlie all others.

studied they have been uncovered by erosion. Such regions may have been more deeply eroded than others because they have been repeatedly uplifted. In the eastern half of Canada the Archæan rocks reach the surface over a large area, interrupted only by bands or patches of the younger rocks. They are exposed again in a long strip between the Appalachian Mountains and the Coastal Plain, stretching from Alabama to New England, in the cores of certain anticlines among the mountains of western United States, and in other situations. In other countries similar exposures of Archæan rock have been found, particularly in Brazil, central Africa, and Scandinavia.

The downward limit of the Archæan rocks is unknown; probably it will never be attained. The upper limit is the surface which separates it from the Proterozoic group.[1]

Complexity of the Archæan. — The study of the Archæan rocks shows that they have been profoundly disturbed and their original form greatly altered. They have been folded, crumpled, and contorted in the most intricate way. They are broken by faults and interrupted by masses of igneous rocks which have been intruded into them. Great batholiths of granite are so common in them as to be almost characteristic of the Archæan system. Study of the intrusions reveals the fact that some have broken through others, showing that they are of many different ages (Fig. 318). Many of these structures have been folded, and broken, since the volcanic activity ceased.

FIG. 318. — Successive intrusions of igneous rock. How do the intrusions rank in order of age?

The known Archæan rocks have been greatly changed. — In an earlier chapter (pp. 67, 77) it has been said that under the tremendous weight of miles of overlying rock even the strongest materials may be crushed, squeezed out into thin plates, and crumpled like leaves of paper. At the same time certain portions of the rocks are dissolved bit by bit and rearranged into new minerals which are better suited to the conditions of high pressure and temperature of the depths. Thus, black basalts become glistening green schists, granites may become gneisses, limestone crystallizes in the form of marble, and shales are transformed into schists spangled with flakes of mica.

[1] By some geologists Archæan is made to include all the rocks below the Cambrian, but this usage is not common to-day.

Almost all the Archæan rocks have been buried to great depths and subsequently uncovered by erosion. The Archæan rocks are therefore commonly schists and gneisses. Certain portions of later systems of rock are likewise schistose, but in the Archæan alone are the schists and gneisses almost universal (Fig. 319).

Metamorphic rocks are of course always derived from other rocks of igneous or sedimentary origin (p. 41). It is often impossible to determine the original character of some of the Archæan rocks, while that of others may be discovered by study. It is a singular fact that among the oldest rocks which have yet been found in the Archæan system are green schists which were once surface volcanic materials, such as lava flows and cinders. These must have been cast out during successive eruptions upon a still older surface, but as yet that surface has not been identified. It is known that some of the gneisses were once granites, — parts of batholiths which were intruded into these green schists, and subsequently metamorphosed.

The Archæan system is not composed entirely of igneous rocks, as it was formerly thought to be. In the Lake Superior region it contains small bodies of iron ore, metamorphosed conglomerate, and slate. In China and Finland even limestone has been found in the oldest rocks, which seem to be of Archæozoic age.

Conditions in Archæan time. — Evidently we can hope to learn but little of Archæan times from such a disordered and obscure record as this, but the very remoteness of that era lends interest to any bit of information about it. Nothing is clearer than that there were many successive volcanic eruptions and intrusions,—probably more than have occurred in any later era. That the weathering and erosion of the lands were already in progress is suggested by the presence of slates and other sedimentary rocks, for slates were once clay and clay is made from many kinds of rocks by chemical decay and the sorting action of water.

Fig. 319. — Contorted schist on the coast of Maine. (Photograph by *Can. Geol. Surv.*)
Are the folds of the competent or incompetent type?

The presence of limestone may mean that shell-bearing animals were already in existence, but the fact that some limestones are even to-day formed by the direct precipitation of lime carbonate from water leaves the question in doubt. Beds of graphite, which are thought to be simply metamorphosed coal seams, indicate that plants lived in Archæan time. No fossils have been found in the Archæan rocks and so we know nothing of the real character of the life which may have existed then. All we can be safe in imagining about the plants and animals of the era is that they were on the average much simpler and lower in the scale of life than those which exist to-day.

Length of the Archæozoic era. — It is difficult to imagine the vast length of time embraced in the Archæozoic era. Since the bottom of the Archæan rocks has never been reached it is clear that we know nothing of the earlier part of that era. Yet even the knowable part gives us a fragmentary story of many successive volcanic disturbances and several distinct periods of folding and metamorphism. From the clearer record of later times we know that such changes take place slowly and are separated by periods of quiet, often to be measured in millions or tens of millions of years. Considerations such as these have led to the conjecture that the Archæozoic era may have been longer than all the later periods together.

Questions

1. In some places the Archæan system is found to contain both gneiss (once granite) and schistose basalt. Which of the two would you consider the older (1) if the gneiss contained rough fragments of the basalt within itself and if the main mass of basalt were cut by branching layers of gneiss, or (2) if the gneiss were crossed by layers of basalt continuous with the main mass of the latter?

2. Why should we not expect to find fossils in schist even though the original mud from which it was derived was filled with shells?

3. An old name for the Archæan system is "Basement Complex." Why is this a good descriptive phrase?

CHAPTER XII

THE PROTEROZOIC ERA

What it represents. — The oldest rocks which contain numerous fossils are those of the Paleozoic group. Between these fossil-bearing sedimentary rocks of the Paleozoic and the intricate complex which records Archæozoic time, there is in many places a thick group of systems, partly sedimentary and partly igneous in origin, which represents a vast lapse of time between these two eras. This time is the *Proterozoic*[1] *era* (often called also the Algonkian period).

Proterozoic Rocks of the Lake Superior Region

The Proterozoic rocks are nowhere better known than in the vicinity of Lake Superior. In certain parts of this region the entire group is divided into four systems which are separated from each other by unconformities. In other localities only three or two divisions are distinguished. Where four systems are known, they are called lower and upper Huronian, Animikean, and Keweenawan.

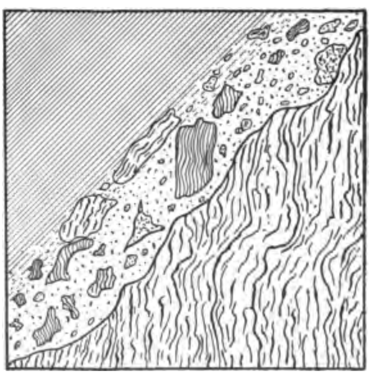

Fig. 320. — Diagram of the contact of Huronian slate with Archæan schist, at a locality in Michigan. (After Van Hise.)

Which is the younger of the two formations, and what is the evidence?

Basal unconformity. — The basal formation may include a conglomerate which contains rounded pebbles of schist and gneiss derived from the Archæan rocks beneath (Fig. 320). No better

[1] From two Greek words meaning "earlier life."

proof could be desired that the Archæan rocks had been folded, metamorphosed, laid bare as land, and profoundly eroded before the Proterozoic rocks were deposited upon them.

Huronian system. — The Huronian rocks are quartzite, limestone, and slate, with the addition of beds of iron ore and jasper. Where metamorphosed the predominating rocks are schists. The beds are usually much folded and they are exposed at the surface as long down-folded bands within the outcrops of the Archæan (Fig. 321). In at least one district a well-marked unconformity divides the Huronian strata into two systems, the lower of which is evidently much older than the upper.

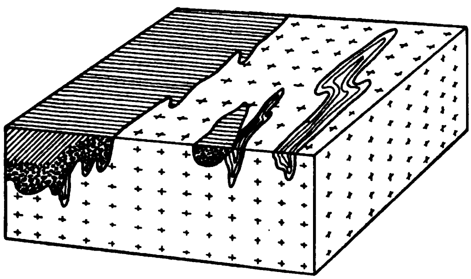

FIG. 321. — Stereogram showing down-folded remnants of Proterozoic rocks surrounded by the Archæozoic complex.

Igneous intrusions of different ages cut through them here and there, and lava flows are sometimes found interbedded with the sediments themselves. Around the batholiths of granite and the other large intrusions, the rocks may be altered to schists; and it then becomes difficult to discriminate them from those other schists which belong to the Archæozoic group.

Animikean system. — Unconformably above the Huronian rests the Animikean,[1] another system of sedimentary rocks and lava flows, which is in general much like the Huronian (Fig. 322). On the average, however, the rocks are less folded and less metamorphosed, — in some places not at all. The quartzites and slates are traversed by a few dikes and larger intrusions of later age. Iron ore has been men-

[1] The geologists of the U.S. Geological Survey class the Animikean as *Upper Huronian.*

FIG. 322. — Section of the pre-Cambrian rocks in northeastern Minnesota. (After Van Hise and Leith, *U.S. Geol. Surv.*) Work out the relative ages of the various bodies of igneous and sedimentary rock as shown in the diagram.

tioned as a constituent of the Huronian. In the Animikean the largest and richest deposits of that indispensable ore that are yet known have been found (Fig. 323). They occur in the form of thick beds in the sedimentary rocks. Some of the Animikean formations originally contained a large amount of iron minerals, together with quartz and other impurities; this was further enriched in certain spots where the underground waters dissolved out everything except the iron minerals and, in some cases, even filled the pores thus left with still more oxide of iron.

The mines of the Lake Superior region supply more than 80 per cent of the ore from which is derived the iron used in the great industries of this country. This is equal to more than one third of the world's output. More ore is now taken from a single mine in the Mesabi district of Minnesota each year than was mined in the entire United States before the Civil War.

Keweenawan system.—Still a third great system lies upon the eroded edges of the Animikean strata and occasionally laps over upon even older formations. In this we have the record of one of the greatest episodes of local volcanic activity known in geologic time. The eruptions seem not to have come from definite craters, but the fluid lava simply welled up through cracks in the surface and spread over wide areas. A series of these flows accumulated one above the other to a depth estimated at more than 6 miles. The great number of the flows may be appreciated when we consider that most of

them were less than one hundred feet in thickness. Later in this period the eruptions apparently came at wider intervals, and meanwhile coarse sandstones were deposited in the same region. Finally the lava ceased to flow out and so, toward the close of the period, only sedimentary rocks were made. These lavas and sandstones form the Keweenawan system. Since they were laid down, they have been moderately tilted but not much altered.

FIG. 323.—Distribution of ore deposits in the Proterozoic rocks of eastern United States; iron districts are shown by the black patches, and copper deposits by the crosses.

It appears that the lava originally contained minute quantities of copper. Part of this copper, furnished in solution to the active underground waters, was deposited in certain porous layers in the sandstones and gravels, as well as in the cindery portions of the lava flows themselves. From these enriched bands vast quantities of pure copper have been mined during the last few decades.

PROTEROZOIC ROCKS IN OTHER REGIONS

Rocks of Proterozoic age are found in many parts of this and other continents, but the formations cannot be matched

closely with those of the Lake Superior region. This is true chiefly because the necessary fossils are lacking.

In the Grand Cañon of Arizona Proterozoic strata are again well exposed, but they are unlike the Lake Superior formations in details. The lower walls of the cañon reveal the complex schists of the Archæan. Upon these rests unconformably a tilted pile of sedimentary strata (Fig. 324).

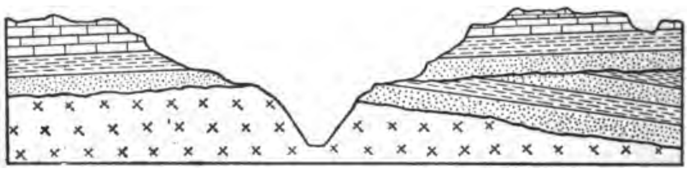

FIG. 324.—Ideal cross section of the Grand Cañon of the Colorado River in Arizona.

In spite of their great age they are neither folded nor notably metamorphosed. These in turn were largely removed during a still later period of erosion, so that the Cambrian sandstone was deposited horizontally, not only upon the beveled edges of the Proterozoic formations, but out over the Archæan also.

Proterozoic rocks are well known in Scotland, Sweden, and China (Fig. 325), and have been studied in considerable

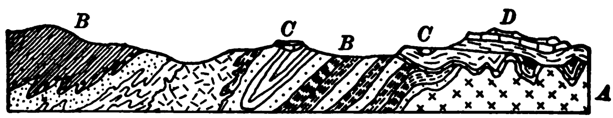

FIG. 325.—A section through the ancient rocks at a point in Northern China, showing the Archæozoic rocks (*A*), overlain by a thick series of folded beds of Proterozoic age (*B*), and upon both resting Proterozoic limestone and shale (*C*), much less folded. The Cambrian rocks (*D*) rest unconformably on the others.

detail. In each case there appear to be two or more systems between the Archæan and the Cambrian, separated from each by a pronounced unconformity. Where there are two systems the older is usually intensely folded and metamorphosed, although still plainly made up of sedimentary rocks;

while the younger consists of slates, quartzites, and limestones which are neither closely folded nor much altered.

General Characteristics of the Proterozoic Group

Sedimentary rocks but with some igneous. — Having learned something about the Proterozoic systems in widely separated regions, we may proceed to consider the things which are characteristic of the group as a whole and of the long periods of time during which it was being formed. In each case the rocks which make up the group were derived chiefly from ordinary sediments. They were once gravel, sand, clay, and ooze spread out upon the sea floor or upon the low-lying lands. They have since been cemented into solid rocks; they have been folded, mildly in some places and intensely in others; and some of them have been metamorphosed into slates, schists, and gneisses. Many kinds of lava have been forced up through them at different times. These either spread out on the surface as flows, or solidified beneath in the form of dikes, sills, batholiths, and other intrusions, which interrupt the stratified rocks and complicate the study of the structure. As would be expected, the older Proterozoic formations are often much more deformed than the younger, because they have passed through more epochs of folding.

The Archæan system, we learned, includes some beds of sedimentary rock, but the vast body of that ancient mass is of either igneous or doubtful origin. In the Proterozoic group, on the other hand, the proportions are reversed, and the sedimentary strata predominate overwhelmingly.

Unconformity general but not universal. — We have seen that in each district where the rocks have been fully studied the Proterozoic group is separated from the Archæozoic by a great unconformity. This clearly shows that the regions had been lands cut down by weathering and erosion until the very roots of the Archæan mountains were laid bare and planed off, — and all this before the Proterozoic sediments began to

be deposited. This unconformity evidently tells of a very long lapse of time between the deposition of the Archæan and Proterozoic rocks, — a time otherwise unrecorded in the rocks which we know. Because of this, and because of the wide distribution of the unconformity, it is generally regarded as one of the greatest interruptions in the geologic record. But no unconformity, however widespread, can exist all over the globe. The very same facts which indicate that the lands were deeply eroded prove that the material worn off was as continually being deposited elsewhere; and in those areas where deposition was in progress no unconformity resulted. It has been suggested that the sediments which were deposited then, as now, in the deep ocean basins have never been raised into land, and hence are still unknown to us.

Unconformities within the Proterozoic group. — Other notable unconformities serve to divide the Proterozoic into two or more systems. In Minnesota the Animikean sandstones and shales rest at a moderate inclination upon closely folded slates and quartzites of the Huronian. Furthermore, some of the dikes in the Huronian rocks do not pass up into the Animikean system. Such an unconformity is conspicuous when it can be seen in the side of a quarry or a ravine. No one of these interruptions in the strata has, however, been traced across any continent, much less over several continents; and the divisions themselves, therefore, can be used only in the region where they are known to apply. Proterozoic rocks are generally separated from the Cambrian system, which overlies them, by another great unconformity, a description of which will be found in the next Chapter.

Duration of the Proterozoic era. — Just as the remote ancient periods of human history are long in comparison with the subsequent centuries, so the Proterozoic era was immensely long as compared with later periods. In the course of a century only a few feet of average sediments are deposited, and of limestones perhaps not even one foot. Yet the Huronian sediments of Michigan are alone said to be more than

13,000 feet thick, while the Keweenawan lava flows and sandstones may have a thickness of 35,000 feet. If to the time required for the making of these rocks we add the long lapses of time represented by the various unconformities, it becomes evident that the Proterozoic era was one of the longest. By comparing the thicknesses of younger systems it has been estimated that it may have been as long as all the subsequent periods combined.

Life in the Proterozoic Era

Evidence from the sediments. — In the Archæozoic era living things are believed to have been present, but the evidence of their existence is somewhat indirect, for no fossils have been found. Again, in the Proterozoic systems of rocks, we find limestones, this time in thick layers, which may have been made partly of the shells of minute animals, just as more recent limestones have been.

It is well known that coal beds have been derived from compressed masses of the vegetation which accumulates in swamps. Coaly layers and beds of graphite among the Proterozoic rocks probably had the same origin. Still other facts make it almost certain that both plants and animals were abundant throughout the era.

Fossils very rare. — Among the younger strata of the Proterozoic group a few poorly preserved fossils have been discovered. They are the remains of animals, and among them are forms which seem to belong to the brachiopods (p. 298) and the crustaceans (p. 300).

The crustacean group is one of the most advanced of all the invertebrates, and it is therefore somewhat surprising that it should have appeared so early. Few though they are, these fossils justify us in believing that the living world had been in existence for untold ages before the strata which contain them were deposited, and that the slow changes of evolution had already produced some types not altogether unlike those of modern times.

QUESTIONS

1. Pebbles of Archæan schist are often found in the basal layers of the Proterozoic rocks. Under what conditions are schists produced? And what does this tell about the depth to which the erosion of the land had penetrated at this time?

2. What events are recorded by the unconformities in Figures 326, 327, and 328?

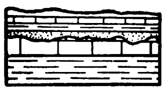

FIG. 326. — An irregular contact between horizontal beds.

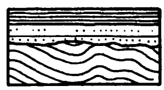

FIG. 327. — Horizontal sandstone resting upon folded beds.

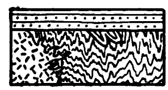

FIG. 328. — Horizontal sandstone resting upon granite, schist, and slate.

3. With which type of volcanic eruption are cinders and ashes usually associated, — the fissure or the crater type?

4. Why should the gravel beds and cindery layers of the Keweenawan contain richer copper ores than the dense lava flows?

5. Why should the older Proterozoic formations be more folded and metamorphosed on the average than the younger?

6. Beds of conglomerate thought to be of glacial origin have recently been found in the Huronian rocks of Canada. With which theory of the origin of the earth is this more harmonious?

CHAPTER XIII

THE CAMBRIAN PERIOD

The Cambrian rocks. — Most of the rocks which constitute the Cambrian system in the United States were originally sands, clays, and oozes, deposited in nearly horizontal layers upon the bottom of the seas of the Cambrian time. That portion of the deposits from which the sea has since been withdrawn and which has been exposed to view by the removal of such younger strata as were deposited on them, was laid down chiefly in the shallow waters near shores. For this reason the clastic sediments predominate in the Cambrian system as we know it. Embedded in these sediments we find the shells of some of the animals which lived in the same seas. The fossils in the lower layers differ somewhat from those found in the upper beds of the system, and by the gradual changes in the fossils from level to level, several stages, or *horizons*, have been recognized within the Cambrian system. A threefold division of the system is usually made, giving us Lower, Middle, and Upper Cambrian series, corresponding to similar epochs of time.

Basal unconformity. — The lowest layers of the Cambrian sediments generally rest upon an uneven eroded surface of the older rocks. In some places the underlying strata are of Proterozoic age; in others of Archæan age. Some of the older rocks were folded or even metamorphosed before the Cambrian strata were laid down. As evidence of this, it is common to find, in the lowest Cambrian beds, pebbles which are waterworn fragments of the older rocks. The unconformity thus indicated has been observed in many parts of the continent, and, as very few exceptions have been discovered, it is evident that before the Cambrian period began, most of North America had been for a time dry land and subjected to ero-

sion. Where the eroded surface of the older rocks has not been deformed by later movements of the crust, it is nearly level; and from this fact it is thought that the denudation of the continent, before the land was submerged by the Cambrian sea, must have continued for a very long time, — sufficiently long to allow the streams to reduce large areas to the condition of peneplains (p. 147). On account of the great duration of this interval of erosion, and because of the very general presence of the unconformity in all continents where the Cambrian has been studied, the interruption is regarded as one of the greatest in the geologic record.

Gradual submergence of the continent. — Further light is cast upon the geography of the times by the discovery that, in North America, the layers which contain the oldest Cambrian fossils exist only near the eastern and western borders of the continent. Farther inland it is the Middle Cambrian that rests on the eroded pre-Cambrian surface; and in the interior, from New York to Michigan, the strata above the unconformity contain the Upper Cambrian fossils. From this we infer that the sea encroached so slowly upon the gently inclined land surface that nearly the whole of the long Cambrian period was required to accomplish the submergence. Not all of the continent seems to have disappeared beneath the sea even at this time. A large area of ancient rocks in eastern Canada, another occupying what is now the Atlantic seaboard, and also some parts of the West seem to have remained as land masses. These continued to be eroded and hence to supply sediments to the seas of the time. The name "Appalachia" is used to designate the large island which then lay just east of the present Appalachian Mountains, from New England to the Gulf states. Its influence on the rocks formed in later periods will be mentioned in succeeding Chapters.

Where seas have encroached upon the land, it is often impossible to decide whether the ocean surface actually rose or whether the lands sank. In the Cambrian, it is significant

that the sea advanced gradually and almost simultaneously over central Europe and eastern Asia, as well as North America. Since continents can hardly be supposed to subside evenly over so large a portion of the globe, the facts in this case suggest a general rise of the ocean waters. The very sediments which were being carried into the sea all through the Cambrian period would inevitably displace a considerable amount of water, and raise the sea level correspondingly.

Cambrian strata differ according to locality. — The Cambrian rocks are by no means alike in all localities, for the conditions of sedimentation varied from place to place. Where the sea advanced over a low shelving surface its waves and currents reworked the soils and alluvial deposits already prepared by weathering and wash, and sifted from them an abundance of sand which was spread widely along the shores. This may be the explanation of the very widespread Middle and Upper Cambrian sandstone which represents the system wherever it is exposed in the interior of the United States. In the West, and in the Appalachian Mountains, the deposits of Upper Cambrian age are principally limestones and shales, indicating that in those districts conditions for clastic sedimentation along shore had passed. During much of the period the water may have been too deep to receive the coarser sediments, but it is more probable that the lands were low and remote, and were for that reason unable to furnish much débris. Owing to the differences in the conditions of sedimentation and in the time it continued, the total thickness of the Cambrian strata is in some places great and in others small. Over the flat interior region the sea was apparently shallow and came in late in the period, so that the sandy formation (Potsdam sandstone) then produced is rarely more than one thousand feet thick. In some places, on the other hand, as in the Appalachian Mountains and in Nevada, deposition of varying sediments seems to have continued nearly or quite throughout the period, and to have resulted in a succession of strata several thousand feet in depth.

Shifting of volcanic activity. — In striking contrast to the Keweenawan system, the Cambrian rocks of North America contain scarcely a trace of volcanic materials. As later periods are studied it will be seen that volcanic activity is prevalent in one region for a time and then dies out, only to break forth again in some other district. So in the Cambrian period, Wales and Scotland, to-day entirely without volcanic activity, were the scenes of many eruptions.

Later changes in the Cambrian rocks. — The sediments of which we have sketched the origin have since been changed in various ways. Almost all have been converted into firm rocks: the ooze into limestones, the muds into shales, and the sands into sandstones or even quartzites. Along both the Atlantic and Pacific coasts they have been in part metamorphosed into slates, schists, and gneisses by exceptional compression and at the same time their fossils were obliterated.

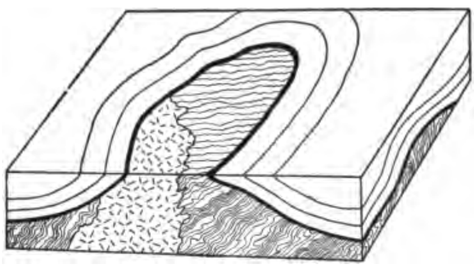

Fig. 329. — Block diagram of a dome fold like that of the Black Hills of South Dakota, showing the relation of the Cambrian (solid black) and later sedimentary rocks to the highly folded rocks of pre-Cambrian age.

Wherever the sea is, there sediments are being deposited; and to these must be added the débris laid down in lakes and other low places. The rocks of any period therefore originally formed a layer somewhat more extensive than the seas of their time. Most of that blanket of rock which we call the Cambrian system is still beneath the sea or, if raised above it, remains concealed by the formations afterwards laid upon it. Around the borders of the old Cambrian lands the system now outcrops in an irregular band adjacent to the older rocks, and, in certain mountain regions both east and west, the Cambrian has been exposed by the deep erosion of raised or folded tracts.

Cambrian life highly developed. — The existence of life in the earlier pre-Cambrian periods of the earth's history is known only from the indirect evidence of organic sediments and the like, or from the testimony of a few imperfect fossil shells. In the Cambrian rocks, for the first time, we find such shells abundant and varied in form. It would not be unnatural to expect that these early animals and plants would prove to be very primitive in their structure and low in the scale of evolution, — but such is not the case. Of the eight or nine primary divisions of the animal kingdom, all but the highest, the vertebrates, have Cambrian representatives. It is probably not too much to say that more than one half of the development of the animal kingdom was accomplished before the Cambrian. We thus get a hint of the long ages which preceded the time of which the geologic record gives us an intelligible story. In spite of the great development of life before the Cambrian, enormous progress was made in the later periods, and, as compared with the animals which succeeded them, the Cambrian types show many primitive characteristics.

Plants existed. — Concerning the plants of the Cambrian time, little is known; but since plants provide the ultimate food supply of most animals, it is evident that they must have been then in existence. We may perhaps attribute the lack of fossils to the fact that the Cambrian rocks thus far studied are of marine origin, and most marine plants are too soft and succulent to be readily preserved as fossils. Only when in younger strata we come to the deposits made in marshes and rivers by the plants which possess woody tissues, do we find vegetable remains well preserved.

The more prominent animals of the Cambrian. — Two groups of animals, the brachiopods and the trilobites, have left fossil remains in such abundance that they are regarded as the most important of all that numerous assemblage of species which is called the Cambrian *fauna*. The early brachiopods had pairs of small oval or rounded shells which

are commonly ornamented only by concentric lines of growth (Fig. 330). Internally they exhibit the simplest type of brachiopod structure, the spiral feeding arms not supported by hard skeletons, and hence not preserved, and the two shells held together by muscles only, rather than by a solid hinge.

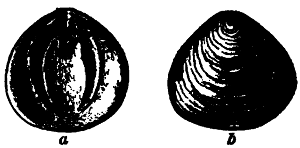

FIG. 330.—*a* and *b*. A Cambrian brachiopod. Interior and exterior views of the shell.

The trilobites had attained somewhat greater variety of form even before the Cambrian period began, and were seemingly more advanced in their cycle of evolution. Some very simple types (Figs. 331 and 332) were present, species which were eyeless and had only two body segments between the broad head and tail. Others were of large size (even exceeding two feet in length, in exceptional instances) and were ornamented with spines and raised lines (Figs. 333 and 334). Most of them possessed prominent compound eyes not unlike those of insects, and they were provided with a generous number of jointed legs of a type adapted to swimming. These crustaceans, by virtue of their advantage in size and their greater intelligence and activity, doubtless held the dominant place in the animal world of their day. Many other groups, such as the corals, mollusks (Figs. 335 and 336), worms, and graptolites, have left representatives among the fossils of the Cambrian strata, but they scarcely attained prominence until later periods. As yet we have no knowledge of the existence in the Cambrian of air-breathing animals, such as insects, nor of even the simplest vertebrates.

FIG. 331.—One of the earliest and simplest trilobites (Agnostus), characteristic of the Cambrian rocks.

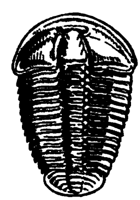

FIG. 332.—A larger Cambrian trilobite (Conocoryphe). Compare this with Silurian varieties. In which are the eyes visible?

Climate of the Cambrian period. — In the days when the Laplacian or gaseous theory of the earth's origin was generally accepted as true, it was thought that, in a period so remote as the Cambrian, the atmosphere must have been distinctly warmer, more moist, and more heavily charged with carbon dioxide than now. There was no direct evidence, however, that such conditions really existed, and in more recent years some facts have been discovered which effectually show that they did not. Glacial deposits of early Cambrian age exist in Norway, China, and probably elsewhere. In China the glaciers were not far from sea level in about the latitude of New Orleans. From this it is reasonable to infer that the general climate of the earth in the Cambrian period was not radically different from that which prevails at present.

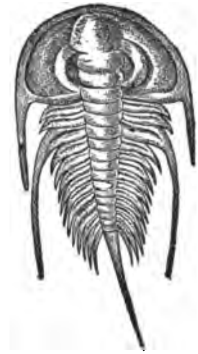

FIG. 333. — A large trilobite (Olenellus) characteristic of the lower Cambrian rocks.

FIG. 334. — A large trilobite (Dikelocephalus) characteristic of the late Cambrian rocks.

FIG. 335. — Supposed pteropod shells (Hyolithes) in a bit of Cambrian shale.

FIG. 336. — A cap-shaped gastropod from the Cambrian system (Stenotheca).

Close of the period. — The Cambrian system is somewhat arbitrarily set off from the Ordovician because of a difference in the fossils which the rocks contain. It is probable that, when the history of the two periods is better known, a more rational means of separation will be found.

Estimates of the length of the Cambrian period. — There is no satisfactory means of determining the number of years in any of the geologic periods.

Nevertheless calculations, based chiefly on the thickness of sediments deposited, give a rough approximation to the truth, sufficient to show that geologic history is exceedingly long. It has been estimated that from 2,000,000 to 3,000,000 years would be necessary for the deposition of the sand, mud, and ooze which formed the thick Cambrian strata. Similar estimates made for later periods indicate that the majority of them were of some such duration. Their combined length must then have been many millions of years, a lapse of time almost too vast for comprehension.

Questions

1. How can the extent of the sea at a particular time in geologic history be ascertained?

2. Why should limestone be deposited close to the shore of a low, densely forested land, but not near a rugged or less verdant coast?

3. Why should the Cambrian system be thicker on the average where it is made up of sandstone and conglomerate than where it consists largely of limestone?

4. Over which kind of a surface would a rising sea spread most rapidly, a peneplain or a mountainous plateau? Why?

5. At several points in the interior of the United States the basal layers of the Cambrian sandstone contain great angular bowlders of quartzite, granite, and other rocks. What do these indicate about the Cambrian shore line at those particular places?

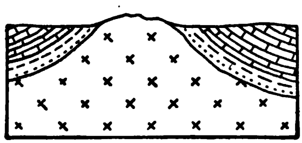

Fig. 337.

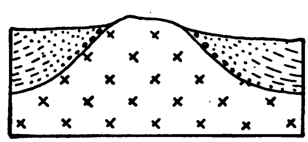

Fig. 338.

6. Compare the diagrams, Figures 337 and 338. In which do you find evidence of the existence of an island in the Cambrian period? Can you suggest how the other has come to resemble it in general structure?

CHAPTER XIV

THE ORDOVICIAN PERIOD

Expansion of the sea in North America. — By the end of the Cambrian period the sea had overspread the greater part of North America. Neglecting certain retreats and readvances of this sea, the salient fact is that the general submergence seems to have been greatest during the Ordovician period (Fig. 339), gradually giving place to the reverse tendency toward the close. On the east side of the continental sea lay the island of Appalachia, an extensive land stretching from New England to the Gulf states entirely east of the present Appalachian ranges. Westward from this island an open sea spread over the interior of the continent, probably joining the Pacific. Some interrupting islands, whose outlines are imperfectly known, are thought to have existed in the western part of the country. On the north lay other lands now represented by the ancient rocks of eastern Canada and adjacent parts of the United States. That much of this sea was shallow is indicated by the remains of corals of the reef-making type and other animals which to-day are unable to live in deep water. Such a shallow body of salt water lapping up over the continent is termed an *epicontinental sea.* Many single species of Ordovician fossils are found alike in Europe and in the United States, a fact which seems to mean that it was possible for the animals of the shallow waters to migrate freely from one continent to the other. As some of these animals find it almost as difficult to cross the deep parts of the ocean as to pass a barrier of dry land, we may suppose that the shallow sea which spread over parts of Canada was directly connected with the similar sea of northern Europe.

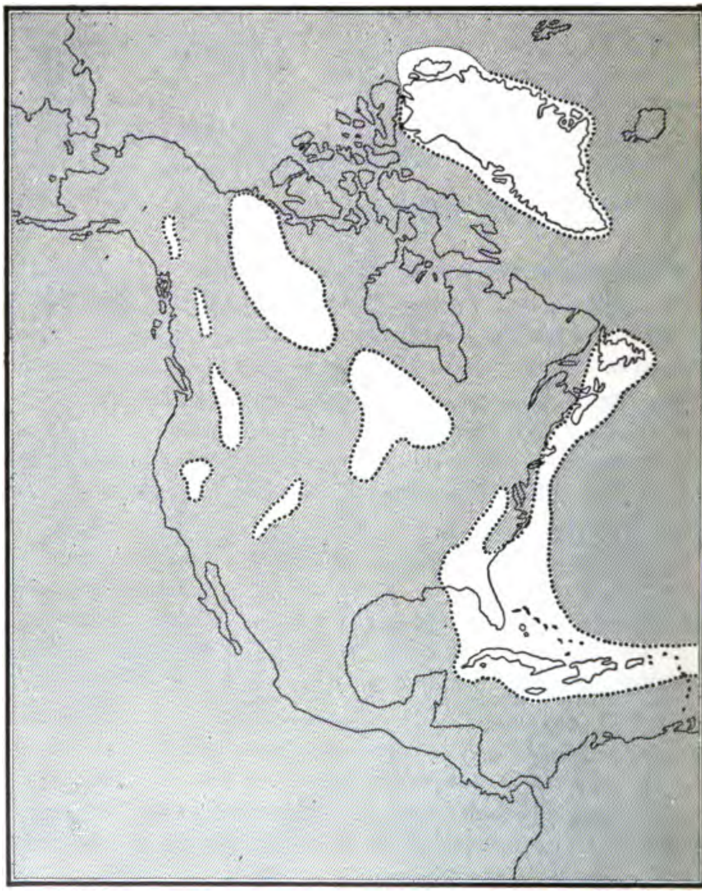

FIG. 339. — Approximate distribution of land and sea in North America in the middle of the Ordovician period. (Modified after Willis.)

Sedimentation under varying conditions. — In different parts of this interior sea the conditions were not alike, and hence the sediments are not the same in different localities. Over the great central and western interior region limy ooze, composed partly of the shells of animals, was the most important sediment, and there we now find thick beds of limestone.

This implies clear water, for, although shell-bearing animals are often abundant in turbid waters, their remains are there mixed with so much mud or sand, that shale or sandstone is the resulting rock. Thus along the western flank of Appalachia there is less limestone in the Ordovician system because the land supplied greater quantities of sand and clay.

Where lands are high they are more rapidly eroded, and when the mountains are near the sea a correspondingly rapid accumulation of coarse sediments is likely to take place off shore. When, however, broad low plains clad with vegetation border the seas, it may happen that little material is worn from the surface thus protected, and likewise little sediment may be washed into the sea in that vicinity. Such considerations as these serve to explain the fact that the period is represented by over 4000 feet of strata in eastern Tennessee, but by only a few hundreds of feet in Missouri. Similarly, there may be differences in the rate at which calcareous sediments accumulate, for in warm, shallow waters shell-bearing animals are likely to be far more numerous than in cold waters and far from shore.

Subsequent changes in the sediments. — The Ordovician sediments were laid down in nearly horizontal beds, and were almost entirely buried by sediments deposited at a later time. Since then they have been consolidated into hard sandstone, limestone, and shale. In some places they have been folded or bulged up in such a way that they have been uncovered by the erosion of the land. Thus the outcrops of Ordovician rocks are now found adjacent to those of Cambrian age. In the Appalachian Mountains these outcrops lie in parallel bands, while on the other hand they form rings about certain upraised masses of older rocks in the northern and western states, as in the Adirondacks, in Missouri, and in the Rocky Mountains. On the Pacific coast, as well as in New England, the Ordovician rocks have been severely metamorphosed, so that it is now a matter of extreme difficultv to distinguish them at all.

Lead and zinc deposits. — In parts of the Mississippi valley ores of lead and zinc are now found abundantly in the Ordovician limestone. Apparently minute particles of lead and zinc minerals were deposited sparsely through the sediments while they were accumulating, and, at a later time, these scattered particles were dissolved out by the waters which saturate the rocks, and were redeposited along joints and bedding planes in the limestone (Fig. 340). Thus concentrated in veins, the minerals may be profitably mined.

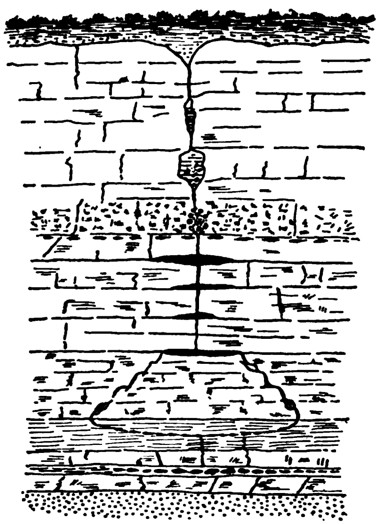

FIG. 340. — Vertical section of a zinc-and-lead ore deposit in southwestern Wisconsin. (After Chamberlin.)

Wide distribution of the sea life. — The broad, shallow seas of the Ordovician period afforded a congenial home for many species of marine organisms, and, although it is certain that the majority of the forms which existed then have left no traces in the rocks, yet enough have been preserved to show us the variety and advancement of the animals of the time. The wide expansion of the seas, and the free communication which seems to have prevailed between them, permitted the individual species to migrate readily from one part of the globe to another. This was particularly true of animals which floated in the water, such as graptolites and young corals (p. 296). Hence some of the Ordovician fossils of the United States are much like those of Europe and even Asia and Australia. Such a widespread assemblage of animals is called a *cosmopolitan fauna.* In any one place the animals of Ordovician time were in part

descended from those which lived there in the Cambrian period, and in part from others which had come in from elsewhere.

FIG. 341. — A characteristic Ordovician brachiopod (Orthis).

Progress of the brachiopods and trilobites. — Among the members of this fauna the brachiopods and trilobites still held a prominent position. The little oval varieties of the former were at this time associated with larger types, many of which were ornamented with radiating ridges (Fig. 341). The species that had hinged shells were more numerous and even the spire-bearing group was represented (Fig. 342). During the Ordovician period the trilobites had risen rapidly to their culmination, and were even more numerous than in the Cambrian. As we shall see, it was not until the next period, however, that they exhibited to the fullest their propensity for adopting queer forms and ornaments. Some of the Ordovician trilobites went to the extreme of simplicity (Fig. 343) in their adornment; a few are quite smooth, and are all but devoid of even the pair of furrows (Fig. 344) which impart to most members of the group their trilobate aspect.

FIG. 342. — A common Ordovician brachiopod with hooked beak (Rhynchotrema).

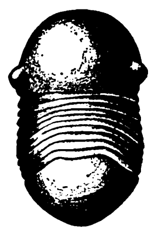

FIG. 343. — A remarkably smooth trilobite (Bumastus) from the Ordovician rocks.

FIG. 344. — A relatively smooth trilobite (Isotelus) of the Ordovician period. Compare the eyes with those of Cambrian types.

New groups of animals appear. — In addition to the brachiopods and trilobites, other groups rose to prominence in the Ordovician. Some were repre-

sented in a subordinate rôle in the Cambrian fauna, while others seem to have made their appearance after the close of the period. Of these none is more important than the graptolites (Figs. 346 and 347), those colonies of little polyps strung on stems. Being freely floating animals they were easily transported by ocean currents, and hence single species had an almost world-wide range. Their relatives, the corals, here became important for the first time. It is to be noted that in the early stages of their evolution the corals were represented chiefly by the solitary hornlike forms (Fig. 348), whereas the habit of living in compact colonies (Fig. 349) became more prevalent in later periods, until to-day the compound corals far outnumber the solitary varieties.

FIG. 345.—Head of a very simple crinoid of the Ordovician period.

FIG. 346.—A colony of graptolites. Each little tooth on the blades held an individual polyp. The central portion may have served partly as a float.

The mollusks (p. 298), of which only the pteropods and cap-shaped gastropods had been noteworthy in the Cambrian,

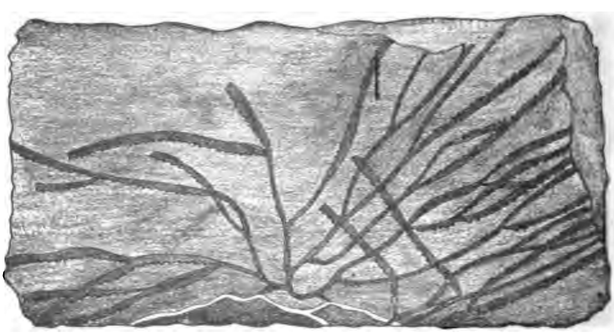

FIG. 347.—A branching colony of graptolites impressed upon a piece of shale.

subsequently expanded into considerable diversity. The gastropods developed many variations of the spiral (Fig. 350) and flat-coiled shells (Fig. 351), lacking in fact only the ornamental spines and tubercles of our modern species. The two-shelled mollusks, or pelecypods, seem to have made slower progress; yet there are many of them in certain Ordovician rocks (Fig. 352). Like the brachiopods, they first appeared with simple unornamented shells, gathering complexity of structure and decoration as they advanced. The highest, and in some respects the most remarkable, group of mollusks, the cephalopods, makes its first appearance in numbers in the Ordovician strata. The earliest types had straight tapering shells (Fig. 353), open at the larger end and divided by sagging partitions into a series of chambers. A seeming advance is shown in curved (Fig. 354) or even tightly coiled shells (Fig. 355), which appeared at this time. The remarkable folding of the dividing partitions did not, however, set in until the Devonian.

Fig. 348. — A small horn coral (Streptelasma) from the Ordovician limestones.

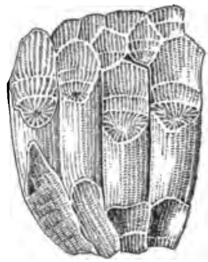

Fig. 349. — Broken fragment of one of the earliest compound corals, showing several coalescent tubes each built by an individual coral animal.

Fig. 350. — An Ordovician gastropod (Hormotoma) with tall, spiral shell.

Fig. 351. — A stout flat-coiled gastropod (Bellerophon) common in the Ordovician period.

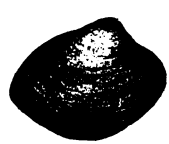

Fig. 352. — A small, plain pelecypod (Ctenodonta).

There is evidence that the great vertebrate branch had become distinct as early as the Ordovician period, for scales, which appear to be those of fishes, have been found in rocks of that age in the Rocky Mountains. Still another long period must be passed, however, before fishes come into prominence.

FIG. 353.—One of the earliest and simplest cephalopods (Orthoceras).

Land plants and animals.—Considering the fact that the continents were so largely submerged and that the known Ordovician strata in which our only record of the life is preserved are of marine origin, it is not surprising that the land animals and plants of this period are scarcely better known than are those of the Cambrian. An insect's wing from the rocks of Sweden proves that the land-inhabiting arthropods had already come into being, and it adds confirmation to our previous suspicion that land vegetation existed in those early times; for the winged insects are almost wholly dependent upon plants for their sustenance.

FIG. 354.—Broken cast of a curved Ordovician cephalopod (Cyrtoceras). Compare the sutures with those in Figures 391 and 418.

FIG. 355.—A coiled Ordovician cephalopod related to forms still living.

Crustal disturbances at the close of the period.—The long, quiet reign of the epicontinental seas, which had begun in the Cambrian and continued through the Ordovician, was partially interrupted by events

which are used to mark the close of the latter period. It is believed that, during ages of tranquillity of the earth's surface, the forces which at times produce warping and mountain folding accumulate power until finally the resisting strength of the rocks is overcome, and the outer layers are wrinkled and broken. This wrinkling is usually confined to a small belt or district, but within that area the folding and crushing may be intense. In the present instance the first premonition of a change is afforded by the fact that the clear seas of the Middle Ordovician in eastern United States later became turbid with mud, so that the last strata of the system are shales overlying the limestones. Evidently changes in the activities of rivers or currents, or both, were in progress, although it is not easy to prove just what the changes were. In eastern New York the early Silurian strata are found lying unconformably upon highly folded rocks which are known to be of Ordovician age. From this it is known that the recently deposited Ordovician and older strata, in that region and somewhat farther southward, were intensely deformed; and also that the same region became land and was subject to long-continued erosion. The wide extent of the unconformity shows that much of the eastern interior of the United States emerged at the same time.

During the compression of the rocks in the East, shales became schists, and fossil-bearing limestone was altered to marble in which nearly all trace of fossils has disappeared. The local nature of this disturbance becomes evident when it is found that in the adjacent regions of New York and New Jersey the Ordovician rocks were only slightly disturbed at this time, while in some portions of the Mississippi Basin they did not even emerge from the sea. The obvious result of the folding must have been a belt of mountains, perhaps of notable height. Although these have since been totally cut away by the erosive agencies, their site is occupied by the newer Taconic Mountains of to-day, and so this disturbance which

closed the Ordovician period is frequently spoken of as the "Taconic revolution."

Similar events in Europe. — In Europe the deposition of sediments in Ordovician time was in many ways like that in the United States, and at the close it suffered a similar interruption. The rocks of Wales and Scotland were highly folded into a series of mountains which were gradually worn down during the Silurian period. The fact that the crust was simultaneously wrinkled on both borders of the Atlantic Ocean suggests that a slight subsidence of the great oceanic area may have been directly responsible for the disturbance. Yet it cannot be said that this is proved.

Questions

1. Sun cracks have been found on the bedding planes of the Lower Ordovician limestone in the Mississippi Valley. From this, what do you infer as to the depth of the water in which this limestone was deposited? How does this compare with limestones in general?

2. Judging from what you know of the Archæan and Algonkian systems, what was the character of the rocks from which the Ordovician sediments were derived? Why does the Ordovician system consist of limestone, shale, and sandstone, rather than pieces of these older rocks cemented together?

3. What is the chief process of change at work on the surface of a land which is too low to be eroded by streams?

4. Can you suggest why nothing is known about the sediments which were deposited in the Ordovician period off the eastern shore of Appalachia?

5. What phase of metamorphism would be most likely to obliterate all traces of fossils in the Ordovician rocks of the Taconic Mountains?

6. Can you see any reason for thinking that vertebrates were in existence long before the fishes whose plates have been found in the Ordovician rocks?

CHAPTER XV

THE SILURIAN PERIOD

Transition from Ordovician to Silurian. — In eastern United States and western Europe the Ordovician period seems to be distinctly set off from the Silurian by the so-called Taconic revolution. Elsewhere, however, the transition from the one to the other was quiet and not marked by notable disturbances. Some portions of this continent emerged from the sea and became low plains, from the surfaces of which little débris could be eroded. In Oklahoma, on the other hand, and in the western states generally, the surface appears to have remained submerged beneath the sea. These things are clearly shown by the succession of the sedimentary rocks. Thus, as mentioned on a preceding page, the Silurian strata lie in marked unconformity upon the folded Ordovician rocks in the New England region. In Tennessee, Minnesota, and some other states, the two systems are parallel in bedding, but are separated by an irregular weathered surface which is in reality an unconformity. In Utah and Montana the Silurian system is only a part of a thick succession of limestones which contain Ordovician fossils below and Devonian fossils above.

Clastic sediments along the eastern land. — The oldest sediments referred to the Silurian period are unlike in different parts of the country. Along the western flank of the newly made eastern highlands quantities of gravel and sand brought down by swift rivers were spread out in thick banks which thinned toward the west. The gravel, now consolidated into hard conglomerate, is known as the *Oneida formation.* Where it has since been tilted up on edge it forms mountain ridges, because the softer rocks on each side of it have been more

rapidly removed by erosion. The sand and finer sediments sifted from the gravel were carried farther westward, forming the *Medina sandstone*. As the high lands were worn down, the rivers became less active, and less gravel was strewn along the front of the mountains. As the zone of gravel accumulation became narrower, the zone of sand deposition encroached upon it, and it thus happened that the Medina sands extended continually farther and farther eastward until they came to lie partly upon the Oneida beds (Fig. 356).

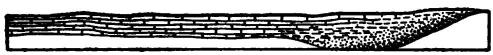

FIG. 356. — Diagram showing the relation of the Silurian limestone in the Mississippi Valley to the conglomerate, sandstone, and shale in New York.

The Clinton iron formation. — In the more remote parts of the interior this rejuvenation of the New England region seems to have exerted no influence. In Illinois, for example, the first Silurian beds were of shale and limestone, and the deposition continued without change in the character of the sediments until the latter part of the period. Between the sandy coastal plain and this clear, open sea there was an irregular belt over which sediments rich in compounds of iron were deposited on a large scale. This phase of the Silurian rocks has been named the *Clinton formation*. The iron ore is usually of the red variety or *hematite;* in some places, where massive beds several feet in thickness are found, productive iron mines are located. The microscope shows that some of this ore has the structure of limestone, — that is, the rock is composed of bits of shells, corals, etc., but the material is largely iron oxide instead of lime carbonate. Students of the subject are not yet agreed as to the exact conditions under which these unusual deposits were made, but there seems good reason to believe that the sediments were laid down in shallow water not far from land.

In the process of smelting iron ore it is mixed with limestone and coke, and when the mixture is heated in the furnace, the iron is released from the ore and flows out into the molds. At Bir-

mingham, Alabama, Clinton iron ore, coal, and limestone are found together. This fortunate combination has made that region one of the great centers of the iron and steel industry, and a place of much importance in the industrial upbuilding of the southern states.

The interior sea again enlarged.— As the period progressed, the sea seems to have encroached slowly upon the land, much as it did during the Cambrian. One broad arm extended northward across Canada and perhaps into the polar regions. As the lands were worn lower and the shores advanced eastward in the United States, the zones of deposition migrated accordingly, so that not only did the Medina sandstone come to overlap the Oneida conglomerate, but the limestone of the West, with its peculiar iron-bearing shoreward phase, overspread the Medina as far as central New York. From the fact that its massive layers form the cliff over which the Niagara River plunges in its famous cataract, the limestone is known as the Niagara formation. It is, of course, much thicker in the Mississippi Valley, where it seems to have accumulated through most of the period, than in the New York region, where it began to be deposited considerably later. The Silurian furnishes an illustration of the well-known fact that a single rock formation in one part of the country may be equivalent in time to several distinct and unlike formations in another place.

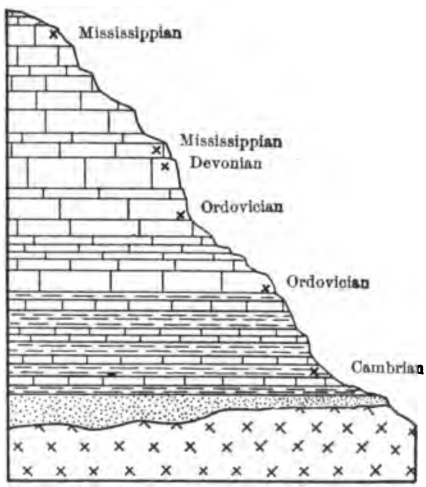

FIG. 357. — Diagram of a limestone cliff in Montana, showing levels (x) at which fossils of different ages were found.

How may the absence of Silurian fossils be explained?

In western North America the Silurian system, where found, consists of limestone. It is in fact merely a part of a thick limestone series which contains faunas characteristic of the Ordovician and Devonian periods as well as of the Silurian. The implication is plain that for long periods of time the open sea held uninterrupted sway. In the region including Colorado and part of Wyoming, however, Silurian rocks are unknown and it is possible that here was a land mass in Silurian time.

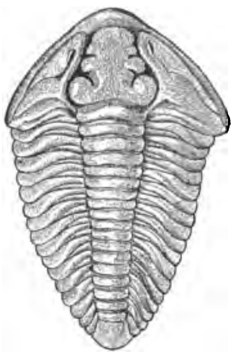

Fig. 358.—One of the commonest trilobites (Calymene) of the Niagara limestone.

Animals of the Niagaran sea. — Our knowledge of the living things of the Silurian is largely confined to the rich and varied society of animals which inhabited the clear though shallow seas of the time. The Oneida conglomerate has yielded no fossils, and the Medina very few, — perhaps because the turbulent and sand-choked streams which distributed them were not attractive to aquatic animals. The Niagara fauna, then, may be considered by itself.

Of the groups mentioned in discussing the Ordovician period all but two made notable progress in the Silurian, the exceptions being the graptolites and the trilobites. The decline of the graptolites from their position of importance in the preceding period was rapid. They are not numerous even in the Niagara rocks, and the Devonian period witnessed their complete extinction. Among the trilobites, however, the descent from supremacy was more gradual. In the Silurian they were still abundant, and never were they more diversified in form than at this time. Like the decadent nations revealed to us in human history, they indulged in extravagant and futile eccentricities, ill befitting their approaching overthrow. Odd and highly ornate forms appeared in profusion (Figs. 359, 360, and 361), and in most instances the

spines, tubercles, and horns which they produced seem to have had little or no real value in their life activities. We

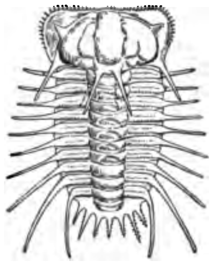

FIG. 359.—An unusually spiny trilobite (Acidaspis) from the Silurian of Bohemia.

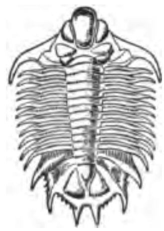

FIG. 360.—A trilobite (Lichas) of the Silurian period. Compare with Cambrian trilobites.

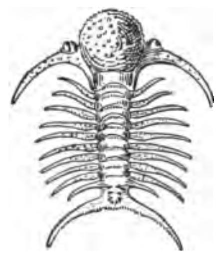

FIG. 361.—A highly specialized Silurian trilobite of peculiar form (Deiphon).

shall see in studying the later periods that similar eccentricities mark the fall of other groups, such as the ammonites and the reptiles.

Among the rising groups only a few require special mention. The corals show an increase in the number of composite types, such as the "honeycomb coral" (Fig. 362) and the "chain coral" (Fig. 363), as against the horn corals. Although the echinoderms had been represented even as early as the Cambrian and had attained some importance in the Ordovician, they did not reach commanding prominence until the Silurian. The clear, shallow seas in which the Niagara ooze was produced furnished congenial life conditions not only for corals but for communities of the crinoids (Fig. 364),—

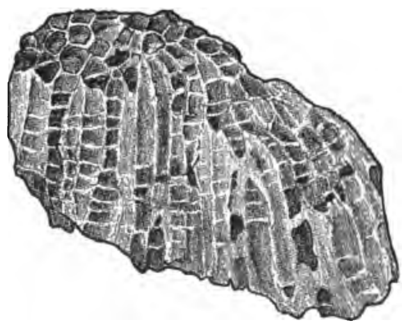

FIG. 362.—A piece of honeycomb coral (Favosites).

graceful animals attached to the sea floor by flexible stalks and provided with feathery arms or tentacles around the mouth (p. 297). The mollusks (Figs. 365 and 367), and their companions the brachiopods (Figs. 366, 368, and 369), developed steadily along the lines already defined in earlier times, and became constantly more numerous. Clearly preserved fishes appear here for the first time, but as yet they are rare, and the consideration of them may best be deferred until the Devonian is discussed. They were extremely primitive types, unlike any that are now living.

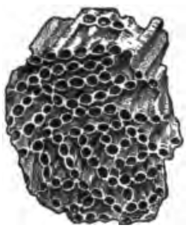

FIG. 363. — The chain coral (Halysites), common in Silurian limestones.

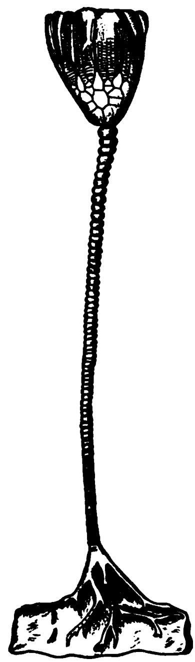

FIG. 364. — A nearly perfect crinoid, as found in the Niagara limestone of Indiana. The roots served merely for attachment.

Life on the lands. — The plants, which we may well believe clothed the Silurian lands, are almost unknown, — doubtless for the same reason that has been suggested to explain the similar absence of information about the *flora*[1] of earlier periods: the known rocks are chiefly of marine origin. Equally scant is the record of air-breathing arthropods, but

FIG. 365. — A stout Silurian gastropod (Strophostylus).

FIG. 366. — A large and strongly beaked brachiopod (Conchidium) of the Silurian period.

[1] The *flora* of a country or of a period is the entire assemblage of trees, shrubs, herbs, and other plants living in that place or time.

the fossils already discovered show that, even before the Silurian period, this group had become divided into its constituent classes, such as insects, scorpions, and others.

FIG. 367.—A coiled Silurian cephalopod (Phragmoceras).

Relations with Europe. — A fauna very similar to that just described lived in a sea which occupied the site of England and the Baltic region during the same time. It is thought that the route of intermigration between the two continents lay along a shallow-water tract which extended up through Canada and Alaska and perhaps even the polar regions. So easy was the communication along this path that peculiar Swedish corals and trilobites found their way over to Iowa, and crinoids characteristic of the United States became residents also of England.

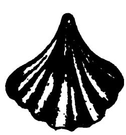

FIG. 368. — A small pointed brachiopod (Rhynchotreta) characteristic of the Silurian rocks.

Silurian deserts. — The quiet continuance of these broad epicontinental seas was interrupted in both continents by changes of far-reaching importance. The deposition of limestone in eastern United States gradually ceased, and, in some areas, if not in all, this was occasioned by the emergence of the sea bottom into a low-lying land. In the West at this time much of the region from Montana southwestward remained under water.

FIG. 369.—A Silurian brachiopod (Orthothetes). One of the flat varieties with a long hinge line.

In the East the Niagara limestone is frequently found lying unconformably beneath the later deposits. In the districts

adjacent to lakes Erie and Ontario, sediments continued to be deposited. While part of the beds were laid down under water, this was evidently not the water of the open sea. The rocks (*Salina* beds) consist of shales and sandstones of reddish and gray colors interbedded with seams of gypsum and rock salt. The salty beds are covered by a peculiar limestone, parts of which are valuable for the manufacture of hydraulic cement, and in this limestone are found, not the Niagara fossils, but peculiar arthropods (Fig. 370) and fishes of types which are almost unknown in strictly marine formations.

FIG. 370.—A large arthropod related to those which are found in the Water-lime formation.

The Silurian salt beds of New York have long furnished a large part of the salt used in this country. Wells have been bored through the overlying strata into the salt beds, and the salty water is pumped to the surface. There the water is evaporated and the salt remains.

At the present time beds of salt and gypsum are produced in excessively salt lakes, such as Great Salt Lake and the Dead Sea. These saline lakes are confined to desert regions where evaporation is rapid. It is significant also that the sediments deposited in some desert basins are of a red or brownish color. From these considerations it appears that, in the late Silurian, northeastern United States had a distinctly arid climate. Most deserts are now situated in the interiors of continents, either where they are sheltered from moist winds by barrier mountain ranges, or where drying winds, like the trade winds, blow constantly. The emergence of the continent which seems to have occurred in the late Silurian largely increased the area of land, and, if highlands of sufficient elevation were so situated as to exclude the moist winds from the Gulf of Mexico and the Atlantic, which now bring rain to the Ontario region, the conditions for local

deserts would have been present. The upper limestone, or *Water-lime* formation, is thought to have been deposited partly in fresh or brackish lakes, which were perhaps made possible by an increase in the rainfall of that region.

Closing incursion of the sea. — In the vicinity of lakes Erie and Ontario, where the Salina beds are best known, the Water-lime formation grades upward into limestone with coral reefs and marine shells. A second incursion of the epicontinental sea is thus recorded. Between these *Monroe* strata, as they are called, and the overlying Devonian rocks there is no sharp dividing line, but merely a gradual change in the kinds of fossils.

Questions

1. Why are the divisions of the Silurian system as recognized in New York not suitable for Illinois?

2. The pebbles of the Oneida formation consist largely of pure quartz. Can you suggest how pure quartz gravel could be derived from a complex mass of igneous and metamorphic rocks such as those which were exposed in the ancient continent of Appalachia?

3. By what process may loose gravel be transformed into a hard rock capable of forming mountain ridges?

4. Why should fossils be rare in the Oneida formation, even if shell-bearing animals were abundant at the time and place it was deposited?

5. At Cobalt Lake, in northern Ontario, the Niagara limestone lies directly upon the surface of Huronian and Archæan igneous rocks. What different hypotheses may account for this relation?

6. Small patches of Niagara limestone are found northeast of the edge of the continuous formation in Canada and the United States. What is the significance of these *outliers* (Fig. 371), as they are called, with reference to the former distribution of the Silurian system?

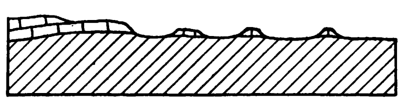

Fig. 371. — Diagram of outliers.

CHAPTER XVI

THE DEVONIAN PERIOD

Relations to the Silurian. — In North America the Silurian and Devonian systems are not sharply separated from each other, either by a striking unconformity or by noteworthy changes in the character of the sediments. For this reason there has been some dispute as to where the division should be made. The fact serves to illustrate the general principle that geologic time itself is unbroken and that the divisions which we recognize must necessarily be somewhat arbitrary and local in their application.

At the close of the Silurian period the great central part of North America seems to have been land. In many parts of the country, — for example, northern Illinois, Alabama, and Colorado, — no sediments of earlier Devonian age exist, and it is thought that much of this area was land at that time. In some other places, as in Iowa, an unconformity has been found at the base of the Devonian system. The detection of this interruption is usually difficult, inasmuch as the beds below are parallel with those above; upon careful examination, however, the irregularity of the contact, the slightly weathered surface of the uppermost Silurian beds, and the abrupt change in the fossils serve to prove the existence of the break. Such an unconformity clearly indicates two things, namely, that the older rocks were not deformed, as were those of New England at the close of the Ordovician period, and that when the sea withdrew it left a land surface of very slight relief. Had the land been high above the sea, the rivers would have cut deeply into it and would either have developed a very hilly surface, or, if the erosion cycle had gone on to old age, the Silurian strata would have been

largely carried off and the Devonian sea would have encroached upon a plain underlain by still older rocks.

North America at the beginning of the Devonian period. — Although this low-lying land seems to have stretched from Michigan and Virginia westward over much of the present Mississippi Basin, the sea had by no means entirely retreated from the continent. In what is now the lower Great Lakes region and again in Utah, Nevada, and Montana, the deposition of limestone and shale went on from the Silurian far into the Devonian. Considering the isolation of these localities, it is not surprising that the fossils in the one place bear little relation to those of the other. No more do the animals which inhabit the seas off California and New England to-day.

Devonian in the West

As the Devonian period progressed, the events in one region were not necessarily the same as those in another. In Utah, for example, lime ooze and mud were deposited uninterruptedly throughout the period, with the result that limestone about 1000 feet thick now represents the Devonian in that region. So free from disturbing influences was this part of western United States that the animals of the western sea underwent only very slow changes. The fossils in the youngest beds of the system do not seem to differ widely from those in the oldest. The conditions elsewhere were in contrast to this.

Devonian in the East

Helderberg limestone. — In eastern United States the period was marked by the gradual reëxpansion of the epicontinental sea, attended by important changes in the relations of the land and water bodies. At first all the eastern lands seem to have been low, for if land masses had been eroded rapidly, the derived sediments would surely have formed clastic rocks in the adjacent seas. As it was, only limestone

was laid down and that chiefly in a restricted sea extending from the St. Lawrence region to Virginia. This is called the Helderberg limestone because it is well exhibited in the Helderberg Mountains of eastern New York. At the same time, apparently, a bay extended up from the south into Tennessee and Indian Territory.

Oriskany sandstone. — As the clear sea with its limey bottom spread slowly westward into the Mississippi Valley and perhaps south to Alabama, some radical change in the middle Atlantic states allowed coarse, sandy sediments to be spread out over the Helderberg formation. The resulting Oriskany sandstone is several hundreds of feet thick, and the sand of which it is made represents the decomposition of a vast amount of solid rock. (How might this be accounted for (1) by climatic change, (2) by diastrophism?)

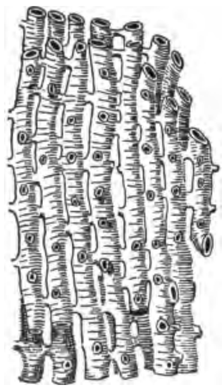

FIG. 372. — A bit of organ-pipe coral (Syringopora) from the Devonian rocks.

Onondaga limestone. — Gradually the deposition of sands became restricted, and the sea which occupied the Appalachian depression was again clear. In it a second limestone, called the Onondaga, was deposited over the Oriskany sandstone. The warmth and shallowness of the Onondaga sea are shown by the abundance of corals (Fig. 372) and other animals which frequent coral reefs. By this time, also, the northwestern part of the continent, from Alaska to Alberta, was covered by the waters of the northern ocean. They were apparently not cold waters in those days, for reasons not yet well understood.

Hamilton shales. — Muddy sediments succeeded the Onondaga deposits in the East, and even in Illinois the limestone is less pure. The Hamilton shales are usually dark and bituminous, implying an abundance of minute plants as well as the animals whose shells abound in the same beds. The

slow decay of these organisms is believed to have produced most of the petroleum and gas which are now obtained from the Devonian rocks in Ontario, Ohio, and Pennsylvania. From the fact that the Hamilton formation thickens as it is followed eastward it seems probable that the mud was largely derived from lands along the present Atlantic slope.

The basins coalesce. — Toward the close of the Devonian the epicontinental sea attained still greater extent. By the spreading of the northwest Canadian sea southward and eastward, the western and eastern basins of the United States seem to have been joined (Fig. 373). In the West and Northwest muds and oozes continued to be deposited, and from this we may infer that in those remote times the western part of America had none of its present rugged mountain ranges, but that it was a flat or undulating lowland. As the upper Devonian strata are traced eastward to Ohio and beyond, they become increasingly thicker and more sandy. We have already learned that a change from ooze to mud and thence to sand is to be expected as one approaches the shore line. The Chemung formation, as these sandy shales are called, grades finally into thick sandstones which contain few fossils except leaves of plants and bones of fishes. It is from these non-marine strata that the Catskill Mountains have been carved. The imperfect assortment of the sediments suggests that they were strewn by rivers rather than by waves, and that the Catskill beds represent the alluvial apron built out into the shallow sea on the west by streams which descended from the highlands of the Appalachian continent.

Migrations and Changes of the Sea Life

As the continuance of the clear sea over a comparatively isolated province such as the Nevada region allowed the animals which lived there to develop quietly along their own lines of advance, so, on the other hand, the shifting relations of land and sea and changing character of the sediments in

eastern United States afforded conditions for the rapid and conflicting evolution of species. At the outset of the period

FIG. 373. — Supposed geography of North America in late Devonian time. The dotted pattern represents sediments on land. The limits of the land mass north and south of the United States are wholly unknown.

the animals of the sea were confined to the edges of the continent and such bays as lapped over its surface. Being iso-

lated, they developed independently, and after the lapse of sufficient time became notably different in the several embayments. As the sea later spread over the land these distinct faunas invaded the interior region from different directions, — one from the northeast, another from the south, another from the northwest, and so on. As the widening seas mingled, the faunas were one by one brought into conflict, much as the invasion of North America by the French and English brought them into opposition in Canada and the Mississippi Valley in the eighteenth century. Just as we now have a mixed French-English people in Quebec, so the mingling of the Hamilton fauna of the East with the McKenzie fauna of the Northwest produced a mixed race in which the influence of the Northwest immigrants was strongest, and left its stamp on the result. The commingling of two marine faunas results in something more than a mere mixture of the two. The struggle between two faunas usually crowds into extinction certain weaker members of each assemblage, and it often results in the rapid rise of entirely new forms not found in either of the original faunas.

In late Devonian times the result of this succession of immigrations and intermixtures was a fairly cosmopolitan fauna inhabiting the seas from Alabama to Alaska and having close relations with the animals of distant China and Russia.

Changed conditions of life. — From what has already been said of the Devonian faunas and their migrations it will be readily inferred that the fossils are abundant and locally well preserved. The same groups which were important in the Silurian are represented also in the next period, although with different relative standings. In the Silurian the animals of the clear seas were almost the only forms extensively preserved. Our best-known Devonian rocks are, however, chiefly shales and sandstones, and so the fossils in them tell us of the animals which frequented the mud banks and the sandy shores rather than the clear, open sea. Conditions which are congenial for one group of animals may be

adverse or even fatal to another. Thus many of the mollusks prefer somewhat turbid water and a muddy bottom, while the corals are exterminated by any large admixture of sediment in the water in which they live. With this principle in mind we shall be prepared to find the crinoids, corals, and other animals which were abundant in the Niagara sea, relatively uncommon in the Devonian formations except the limestones.

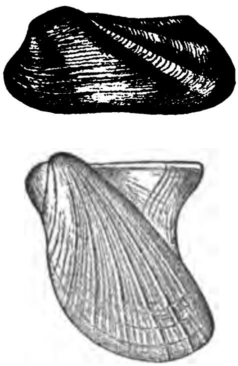

FIG. 374. — Two common Devonian pelecypods.

Mollusks and brachiopods numerous. — Their places were taken by hosts of two-shelled mollusks (Fig. 374) and brachiopods (Figs. 375 and 376), with other groups in subordinate positions. The brachiopods in particular were probably near their zenith in the Devonian. Most of the important types had made their appearance in full force, and it remained for later periods only to carry out the lines of progress already defined.

Fig. 375. — One of the commonest Devonian brachiopods (Atrypa).

Decline of the trilobites. — The trilobites had by this time dwindled to a few forms (Fig. 377) which, however, clung to their Silurian propensity for useless excrescences and ornaments. Although the two cases may not be similar, there is a resemblance to certain decadent families among our own race who cling to the traditions and outward appearances of former rank, long after they have been shorn of power and wealth.

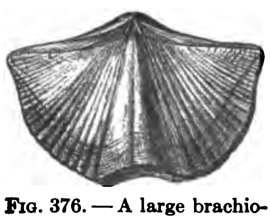

FIG. 376. — A large brachiopod common in the Devonian rocks (Spirifer).

Cephalopods take a new line of advance. — The chambered mollusks, or cephalopods, now enter upon a new career which eventually leads them to the extreme

of complexity and diversification, as regards their internal structure. The early Paleozoic types had shells which were divided into chambers by a series of flat or saucer-shaped partitions. In some of the Devonian species these partitions became slightly folded at their edges, and the suture lines on the outside of the shell show corresponding lobes or angles. These simpler varieties are called *goniatites* (Fig. 378). It will be interesting to compare them with the complex forms of later times.

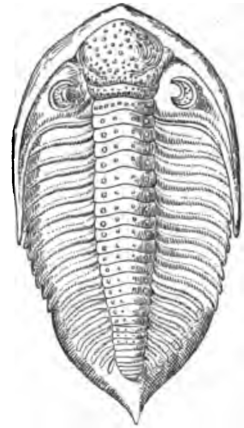

FIG. 377. — A large trilobite (Dalmanites) of the Devonian period.

Profusion of fishes. — Of all the new developments among the Devonian animals, none is more important than the apparently sudden rise of the fishes. From meager beginnings in the previous periods they spread out into many different types, and became so abundant that the Devonian is sometimes called the Age of Fishes. Being among the earliest to make their appearance, it is but natural that the Devonian representatives of the class should have been primitive in their structure.

FIG. 378. — A coiled cephalopod (Goniatites) in which the sutures are slightly folded.

Lowest in the scale are the *Os-*

tracoderms (literally "shell skin"), which were not fishes at all, in the strict sense (Fig. 380). It is not certain that they possessed jaws, but if they did, there is some reason to think that the jaws worked horizontally as in beetles. Strong resemblances to some of the early arthropods are seen in their bony head shields and in the closely spaced eyes. In fact, their claim to a place among the vertebrates rests chiefly on the possession of a tail fin which seems to imply that they had a rudimentary spinal column. Since none are now in existence it is hard to determine their real character.

FIG. 379. — A Devonian coral, showing the cup with radiating partitions.

The true fishes, which are furnished with jaws of the customary type and one or two pairs of fins along their flanks, are represented in the Devonian fauna by many strange and some very large species. Some, on the other hand, were not so unlike those of to-day that the untrained eye would readily note the difference. Others had the head cased in heavy plates of bone, with only the rear part of the body left in a flexible condition. In modern fishes the limb bones do not extend out into the fins, but end in blunt plates to which the fin rays are attached (Fig. 383). The Devonian fishes,

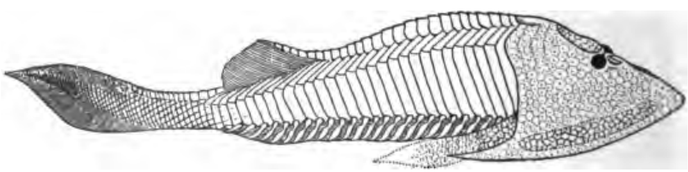

FIG. 380. — An ostracoderm.

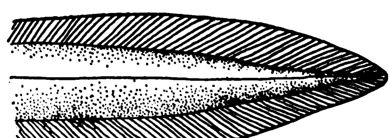

FIG. 381. — Tail of a primitive fish with fringe above and below.

on the other hand, had fully vertebrated fins (Figs. 381 and 382). Again, there are some very peculiar things about the teeth of these ancient members of the finny tribe. Unlike the sharp, spikelike teeth of modern fishes (Fig. 385), many of them were rounded or corrugated plates (Fig. 384) adapted for grinding food rather than for seizing live prey.

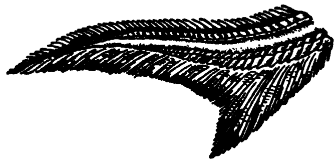

FIG. 382. — Unsymmetrical tail of the sturgeon, in which the body axis follows the upper blade of the fin.

Altogether the Devonian fishes were massive and clumsy. As in the arthropods, their skeletons were chiefly on the outside in the form of bony armor, for the limb bones and spinal column were often little more than cartilage. As time went on, the advantage of speed over armor seems to have led to the strengthening of the internal skeleton with bone, and to the development of a more flexible body.

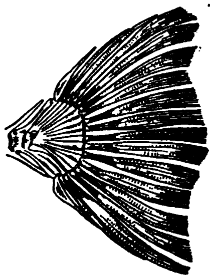

FIG. 383. — Fan-shaped tail fin characteristic of the higher types of fishes.

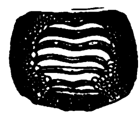

FIG. 384. — A single corrugated tooth of a Devonian sharklike fish.

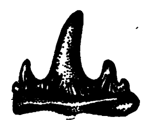

FIG. 385. — Pointed tooth of an extinct shark.

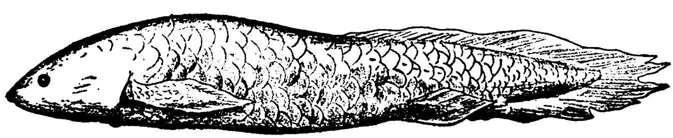

FIG. 386. — A modern lung fish from Australia, not unlike certain Devonian fishes.

LIFE ON LAND

For the first time we have among the Devonian fossils a fair representation of the animals and plants of the lands.

The rivers and other land waters supported a variety of fishes and mollusks. Vegetation was luxuriant in favorable places and included trees as well as the lowlier growths. The trees of this period were not, however, like those of the present day. Most of them were relatives of the ferns. Insects and their allies have been found in some numbers. Considering the small chance of preserving such delicate creatures in the rocks, it would not be reasonable to expect many fossils.

Questions

1. Why is the present distribution of the Devonian system less than it was originally?

2. Can you suggest why the outcrops of the Devonian system are usually narrow bands?

3. Oil is found in Devonian strata in certain parts of eastern United States. It is usually concentrated beneath anticlines. A well piercing the fold usually encounters first natural gas, deeper oil, and still farther down water. Can you suggest why there should be this arrangement?

4. Why should the wells obtain more oil from sandstone than from shale?

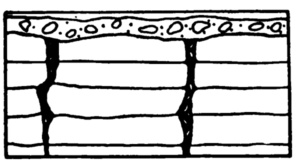

Fig. 387. — Cracks in the Niagara limestone filled with black mud and fossils.

5. An instance is known of the occurrence of black mud containing teeth and plates of Middle Devonian fishes in cracks exposed in a quarry in the Niagara limestone (Fig. 387). Can you suggest an explanation?

6. Under what conditions will two faunas diverge and become less and less like each other?

7. Why should the fossils of the Chemung formation be less like those of the Catskill beds, which are of the same age, than like those of the Hamilton formation, which is distinctly older?

8. Can you suggest why crinoids and corals are rarely found in the Oriskany formation?

9. Why is it not so easy to use the small divisions of geologic time in widely separated countries, as it is to use the larger divisions, such as eras?

10. When a local and a cosmopolitan fauna are permitted to mingle, because of some geographic change, which of the two usually exerts the stronger influence on the new fauna thus formed, and why?

CHAPTER XVII

THE MISSISSIPPIAN PERIOD

The Carboniferous divided. — The Mississippian, Pennsylvanian, and Permian periods were formerly combined under the name of Carboniferous. Evidence is accumulating, however, which indicates that the three divisions are really quite as distinct from each other as are such periods as the Devonian and the Silurian; and so it is thought best to make three separate periods out of the old Carboniferous. Each is named for a region in which the rocks are well exposed and well known.

Transition from the Devonian. — The transition from the Devonian into the Mississippian period was not marked by abrupt changes in most parts of the North American continent. The chief event which characterizes the Mississippian is the further expansion, over the greater part of the United States and the Northwest, of the epicontinental sea which, even in the late Devonian, was fairly extensive. This expansion of the sea was followed later in the period by a corresponding retreat. For the eastern interior, it was the last period of purely marine conditions.

Clastic sediments in the East. — Over what is now the Mississippi Basin, as far east as Ohio, and as far west as Nevada at least, was the open sea. In that portion of this vast region which the Devonian ocean had also covered the strata of the two systems are generally conformable. In much of the West, however, the Mississippian extends beyond the Devonian and rests directly upon more ancient rocks, in some places even on the Archæan. About the northeastern border of this sea, notably in Pennsylvania and Ohio, coarse sands and muds were accumulating rapidly.

The rocks, as we now find them, are thick clastic formations, usually called the *Pocono sandstone* below, and the *Mauch Chunk shale* above. Ripple marks and sun cracks in the shales indicate that they were deposited in shallow water; and a close study of them has recently made it fairly certain that they represent a great flat delta plain over which rivers in a semiarid climate spread silts and sands in times of flood. Occasional coal seams tell of the existence of marshes upon the surface of this delta plain.

Limestone in the central and western states. — As we trace them farther west and south, the land-derived sediments become finer, and limestone increases in prominence. From Indiana westward massive limestones form the bulk of the Mississippian system. The same formation reappears in the Black Hills, parts of the Rocky Mountains, and the Arizona plateaus, and is believed to underlie nearly all of the Great Plains. This extensive limestone series implies a clear open sea remote from rugged lands. That its genial waters abounded in animals of the sea is proved by the crinoids, corals, and other fossils with which the strata are locally crowded. This is true especially in the Mississippi and Ohio Basins, or, in other words, near the border line between the muddy and the limy bottoms. The deep sea explorations of the "Challenger Expedition" some years ago brought out the fact that animals are always extraordinarily abundant near the *mud line* or the outer edge of the muddy area; there the conditions of life seem to be more favorable than elsewhere.

Sedimentation outside of the interior sea. — A body of water covering the southern peninsula of Michigan was at this time more or less isolated from the great interior sea. The strata which accumulated there are associated with salt and gypsum, suggesting that the local climate was not moist, and that the basin was cut off from direct connection with the sea.

Again, in Nova Scotia sediments were laid down in basins

probably not filled by the sea. Thick sandstone and conglomerate are there succeeded by shales with gypsum.

Decreasing seas at the close. — The uppermost strata of the Mississippian in the middle states are shaly and even sandy, like the beds which immediately followed the Devonian. Above these sandy beds there is usually a distinct unconformity, which separates the Mississippian from the overlying Pennsylvanian system. The lower shaly beds we have interpreted as the mud banks along the borders of an expanding sea, in which the deposition of mud was gradually being replaced by that of limy ooze. Toward the end of the period the sea was evidently being restricted in eastern United States. As the shore line migrated west and south, the mud and sand which are usually deposited near shores were spread out over the limestone that had been deposited in the clearer sea earlier in the period. Finally by withdrawal of the sea the eastern part of the country became land. The erosion of this low land was attended by slight warping of the surface, and even a few faults and gentle folds were produced. The result of the disturbance and the erosion together is the unconformity between the Mississippian and Pennsylvanian systems.

In the far West, changes of land and sea at the close of the Mississippian period were less pronounced. No distinct line of separation between the two systems has been recognized in the Arizona-Nevada region; but in the Rocky Mountains a widespread unconformity indicates the emergence of the sea bottom.

The Paleozoic Alps. — During the four preceding periods sediments were being deposited rather generally over western Europe, much as in eastern United States. It is noteworthy that Britain and Germany were also volcanic districts through much of this time.

After the close of the Mississippian period, these deposits were locally folded up (Fig. 388) into two great mountain chains, one extending from Ireland into Germany and the other from southern France into Bohemia. These folds now

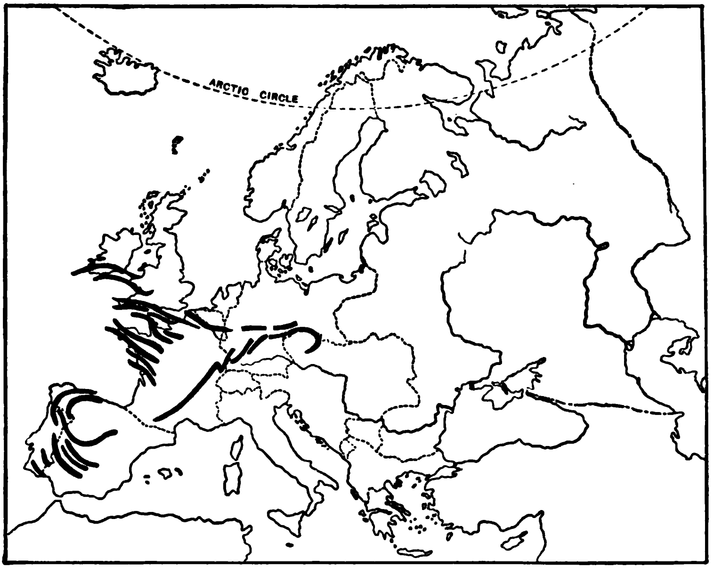

FIG. 388. — Trends of the folds produced during the late Paleozoic mountain-building epoch in western Europe.

are so old that they have been worn down to mere stubs, — such as the low mountains and hills of the Black Forest and Cornwall. But in their prime they may well have been lofty, snow-capped ranges, and for that reason they are styled the *Paleozoic Alps*.

LIFE OF THE MISSISSIPPIAN SEA

On account of the wide extent of the clear Mississippian sea, it is but natural that of all the life of the period we should know the marine animals best. Very few animals and plants of the dry land have escaped destruction, nor are those of rivers and swamps well represented among the fossils of the time.

Abundance of the crinoids. — In the limestones of earlier periods we have noted the abundance of either corals or cri-

noids or both. They were preëminently animals of the clear seas; but the conditions of depth, temperature, and food supply which are essential for one are not quite those which are required for the other. In some parts of the Mississippian sea of the United States, corals seem not to have been favored, although they were common elsewhere. Where the corals were few, crinoids were locally so abundant that some strata are composed mainly of their stems and scattered plates. At no time in their history were the crinoids more diversified or more highly ornamented. Like the trilobites of the Silurian, some of them assumed eccentric and seemingly useless changes of form, with spines, ridges, and knobs upon the plates. Similarly, the crinoids were at this time on the verge of a rapid decadence; by the close of the Mississippian period the majority of them had become extinct, leaving a decreasing line of descendants which are but poorly represented in our modern seas. The cause of their decline is yet a mystery.

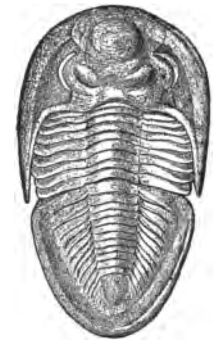

FIG. 389. — One of the last representatives of the trilobites (Phillipsia) found in Mississippian rocks.

FIG. 390. — A complete blastoid. One of the stemmed echinoderms, especially common in the Mississippian limestones.

Development among the fishes. — In the eastern part of the interior sea, fishes were numerous, and, as we may well believe, the most formidable predatory animals of the time. Significant changes had taken place among them since the Devonian. The

FIG. 391. — A Mississippian goniatite with moderately folded sutures.

queer ostracoderms had disappeared, and the heavily protected sluggish types of the true fishes were replaced by more active varieties which relied upon swiftness rather than upon armor. The place of prominence was occupied by the sharks and their relatives, but the Mississippian forms of sharks (Fig. 392) were by no means so formidable as their modern representatives. In those days many of them were provided only with flat, corrugated teeth suitable for grinding mollusks and other small animals. As weapons of defense against predaceous fishes, such teeth were evidently not effective; and perhaps to offset this lack, further protection was added to some varieties in the form of sharp spines on the outside of the body.

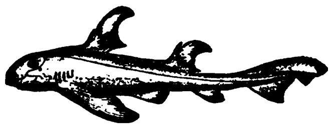

FIG. 392. — The Port Jackson shark. One of the nearest living relatives of some of the Paleozoic sharks. Like them its mouth is paved with grinding teeth.

Advent of the amphibians. — The vertebrates now show a distinct advance in the advent of a class, some members of

FIG. 393. — A modern salamander or tailed amphibian. (Jordan and Kellogg.)

which, at least, were equipped with legs and toes, and were able to live on land and breathe air. As the vertebrates are now predominately land animals, this was a notable step toward the realization of the future destiny of the group. The fossil remains of amphibians are very rare in the Mississippian rocks, and little is known about them. They were long, salamanderlike animals (Figs. 393 and 394), which doubtless spent most of their time in the water. The rela-

tionships between these primitive amphibians and the fishes are so close as to leave small doubt that they were actually derived from one of the groups of fishes in the Devonian. Indeed, even among the highest amphibians the young are hardly more than fishes, breathing water through gills and swimming by means of fins.

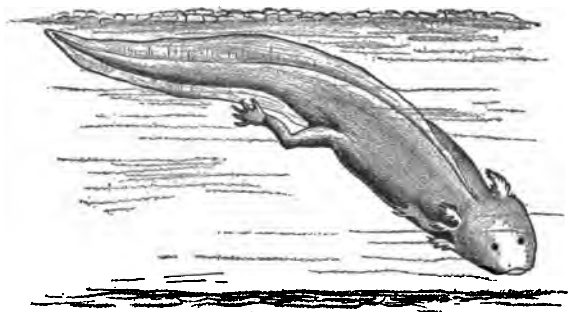

FIG. 394. — Larval form of a salamander, showing the finlike fringe on the tail and the branching external gills just behind the head.

QUESTIONS

1. Many limestones such as those of the Mississippian system contain nodules of flint and chert, — a very dense form of quartz. During the weathering of the limestone what should become of these nodules?

2. What different types of animals could make five-toed footprints? Which of these groups is the lowest in the scale of evolution?

3. An important part of the salt now used in the United States is obtained from Mississippian strata. From your knowledge of the formations of this age, where should you expect to find the center of this salt industry?

4. What structure should you expect to find in the Paleozoic rocks of Belgium? Why?

5. At a locality in Illinois the Pennsylvanian and earlier Paleozoic systems have the relation shown in Figure 395. What events are indicated?

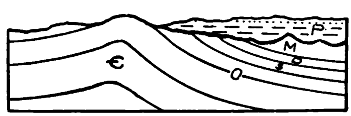

FIG. 395. — Section of Paleozoic beds in Illinois.

6. On what grounds is it justifiable to separate the Mississippian as a distinct period?

CHAPTER XVIII

THE PENNSYLVANIAN PERIOD

THE system which contains the most important deposits of coal in both the United States and Europe is called in America the Pennsylvanian. Because of the great value of the coal beds, this division of the old Carboniferous has received more attention than the earlier and later portions.

Land interval at the beginning. — At the close of the Mississippian, a large part of the United States emerged from the sea, and the fact is recorded by an extensive unconformity. Sediments continued to accumulate in certain low or submerged regions, for example in Arizona and Utah, and there we find transitional formations; but in the eastern interior especially, land conditions prevailed. The long-continued weathering and erosion of the land removed part of the Mississippian rocks, and locally uncovered still older formations. As the limestones crumbled and decayed, a residual layer of clay, with bits of flint which had formed part of the original rock, was left upon the surface. These insoluble grains and nodules, worked over by the currents of the rivers and the sea of the ensuing period, contributed to the formation of the basal part of the Pennsylvanian system.

Marine conditions in the West. — In the Southwest, where changes of geography had been slight, the interior sea had been maintained. Early in the Pennsylvanian it extended itself over a much larger part of the West. In its clear waters limestone was deposited in Nevada, while shales and sandstones are found in Arizona and Montana.

Corals, crinoids, and other marine invertebrates (Figs. 396 and 397) flourished in these waters, as in the preceding age, although the number of fossils which have been found is far

less. We are not to suppose, however, that the West was entirely submerged at this time. Reddish sandstones in the Black Hills of South Dakota and coarse red conglomerates in parts of Colorado were probably deposited upon land by streams. They contain no marine shells. These red strata are linked with the more widespread red beds of the Permian period and with the peculiar conditions of its climate, — a topic discussed in later pages.

FIG. 396. — A brachiopod (Spirifer) from the Pennsylvanian limestone of Colorado.

Transformation eastward.—In the Rocky Mountains the Paleozoic rocks have been exposed by the upturning of the beds (Fig. 450). Traced eastward, they dip beneath Mesozoic strata which underlie the Great Plains, reappearing hundreds of miles away in eastern Nebraska, Kansas, and Oklahoma. Where they reappear the Pennsylvanian system is notably changed. Marine limestones are subordinate, and are interbedded with shales, sandstones, and beds of coal. Still farther east the coal becomes more abundant and the marine strata correspondingly less conspicuous. Evidently the eastern part of the country was not the site of a clear, open sea.

FIG. 397. — A large spiny brachiopod (Productus) of the Pennsylvanian period.

Coal measures of the East. — The Pennsylvanian rocks of eastern United States contain so many beds of coal that they are often called the *Coal Measures.* Only a small part (about 2 per cent) of the total thickness of the system actually consists of coal. The section (Fig. 398) shows

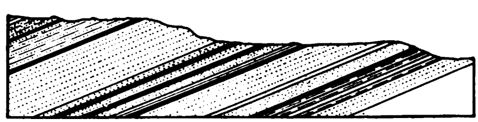

FIG. 398. — Cross section of Coal Measures. The heavy black lines represent coal seams.

that the coal seams, which average but a few feet in thickness, are interbedded with thicker layers of sandstone, shale, and other rocks. The details of this section hold good for a single locality only. Elsewhere we may find fewer or more coal seams, and the thicknesses of the individual beds vary from place to place. But the general relations are typical of the whole region.

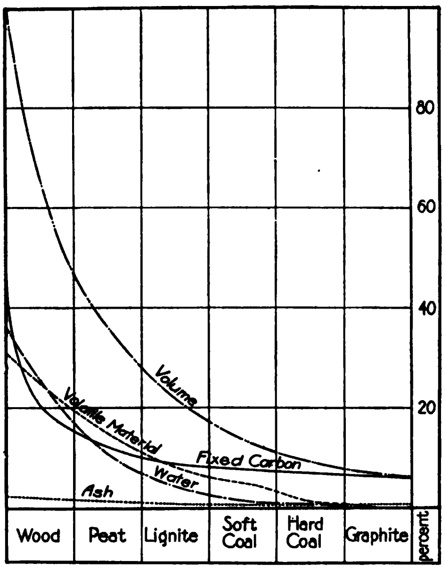

FIG. 399. — Curves showing the changes which take place in the alteration of wood through coal to graphite.

Why so little change in the ash? What proportion of the changes may be passed through while the marsh is still unburied?

Origin of coal. — There is ample proof that coal is composed of vegetable matter much altered from its original condition. Stumps of trees are sometimes found standing in the coal seams as they grew; delicate leaves are matted upon the shales which accompany the coal; and it is often possible to identify, even with the naked eye, the cellular structure of plant tissues in pieces of the pure coal itself.

Vegetable substance is composed chiefly of carbon, hydrogen, and oxygen in very complex compounds. When wood decays, chemical changes take place and new substances are produced. If this decay goes on in the open air, the carbon, hydrogen, and oxygen (most of this from the air) unite in such a way as to form water and the gas carbon dioxide. As these are volatile, the entire substance of the plant soon disappears.

If, however, the tissues decompose under water, where the air is excluded, the changes are quite different (Fig. 399). There is not enough oxygen present to form much carbon dioxide and water. The principal products are a carbon-hydrogen gas, known as marsh gas, and other compounds which contain less carbon. While the bulk of the hydrogen and oxygen are thus removed, the carbon is only moderately reduced, and thus it comes to form a proportionately larger part of the solid mass which is left. The result of this process is coal. (See curves in Fig. 399.)

For the formation of coal, then, two things are needed: abundant vegetation, and decay under water. In forests we have the first condition, but not the second. In the sea, decay takes place under water, but the vegetation is not usually deposited in great quantity. In swamps and marshes, however, both conditions are favorable. That coal has actually come from marsh deposits is plainly indicated by many facts. The seams of coal are basin-shaped, being thickest near the middle, and thinning out into mere black soils at the edges; this is just the shape of existing marshes. Again, we find the old stumps and rootlets embedded in the clay beneath the coal (Fig. 400), showing that the vegetation grew where the coal now lies; and remains of aquatic animals in the midst of the coal tell of the presence of water while it was being deposited. Coal, then, is nothing but the half-decomposed vegetable matter of swamps, long buried by later sediments, compressed by their weight, and converted into a hard rock.

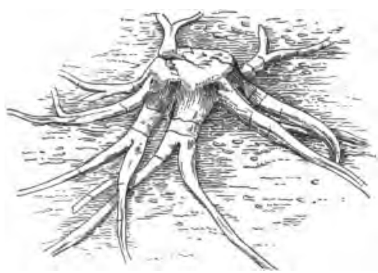

FIG. 400. — Petrified stump and roots of a tree uncovered in a coal mine in Scotland.

Varieties of coal. — The varieties of coal mark stages in the process by which the volatile components are gradually

lost. *Peat* is merely a compressed but spongy mass of carbonized plants, such as we may now find beneath swamps. *Soft* or *bituminous coal* has lost far more of the gases and liquids and is a firm rock. *Anthracite* or *hard coal* is nearly all (91 to 95 per cent) carbon — a hard rock bearing little trace of its origin.

The loss of the volatile parts of the coal is a very slow process. Thus we find that the marsh deposits of more recent periods are but partly converted into coal, while, at the other extreme, the most ancient beds are reduced to impure carbon alone, in the form of graphite. It is not, however, altogether a matter of age. In some places, as in Colorado, igneous intrusions have baked the soft coal[1] into anthracite, or even coke. Wherever the coal-bearing strata have been strongly folded, the coal is found to be much harder than in strata of the same age where they have not been folded. Thus the Coal Measures of eastern Pennsylvania contain anthracite because the strata were crumpled, while in the western part of the state they are flat and afford only soft (or bituminous) coal, the age of the rocks being the same in both localities.

Coal resources of the United States. — The wonderful development of manufacturing in the United States is due in no small degree to the presence of great coal beds in the populous eastern states. No other country, except perhaps China, is so well provided with this essential resource (Fig. 401).

Marshy plain in the East. — Returning to our picture of the United States in Pennsylvanian times, we may think of the eastern part of the country as generally low and monotonously flat. Vast swamps probably bordered the sea which lay to the west, as they now fringe the coast of New Jersey, the Carolinas, and Florida. On the east they were flanked by the land mass of Appalachia. Inland, along the sluggish rivers, fresh-water marshes, like those of the Mississippi and the Yukon, probably covered large areas. Gradual but halting submergence of the region seems to have been in progress.

[1] These particular coal deposits are of much later age.

Now and again the swamps were inundated, allowing sand, mud, and even lime ooze to be spread over them. If the movement soon ceased, the sea bottom was gradually built up by the sediments until the water again became so shallow as to favor the growth of marsh plants. That the sea was not

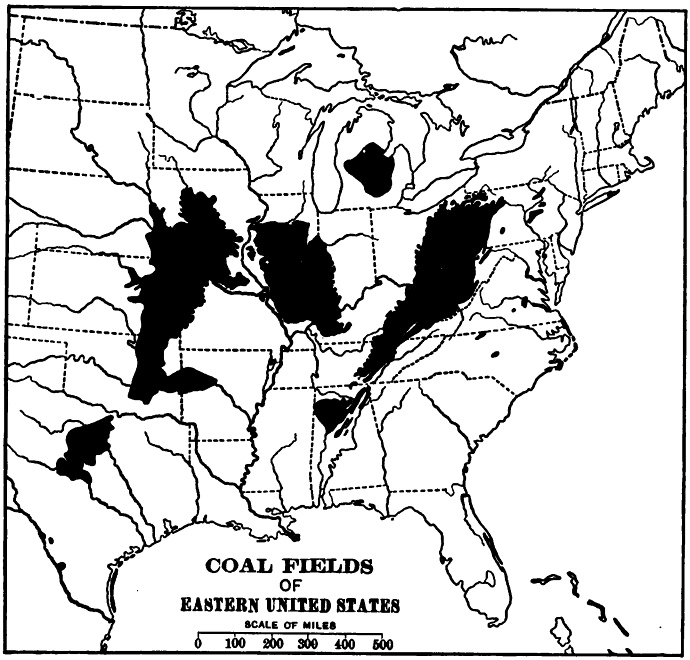

FIG. 401. — The coal fields of eastern United States. Those east of the Great Plains are largely of Pennsylvanian age, but in part Triassic and younger. (*U.S. Geol. Surv.*)

always encroaching on the land is shown by the presence of unconformities in the Coal Measures. While some of these are due merely to the shifting of stream channels traversing the marshes, others imply temporary land conditions during which the rocks were eroded slightly. In short, the land was very near sea level, but was sometimes above it and

sometimes below. During the Pennsylvanian period many hundreds of feet of strata with many distinct coal beds accumulated.

Coal Measures in Europe. — The marshy plains were duplicated on a smaller scale in western Europe; and, from the coal seams there formed, England, Germany, and adjacent

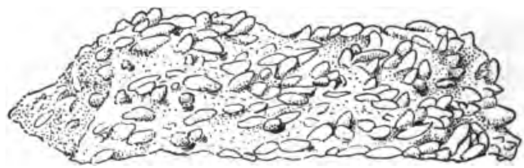

FIG. 402. — Little wheatlike shells of protozoans (Fusulina) in a Pennsylvanian limestone.

countries now derive most of their supply of coal. Russia, the Mediterranean region, and southern Asia, however, were occupied by clear, open seas in which thick beds of limestone were deposited. In some places these strata are so full of the little wheatlike shells of the protozoan *Fusulina* (Fig. 402) that they are generally known to geologists as the "Fusulina limestone."

Life of the Coal Swamps

Plants well recorded. — Plants are known to have been plentiful in the Devonian, and there is reason to believe that they clothed the land surfaces even in much earlier periods; but by the accident of having large coal beds preserved, we have in the Pennsylvanian rocks for the first time a satisfactory record of the plants of the land.

Dominance of the fernlike forms. — As in our modern swamps, so in those of the Pennsylvanian period, plants of all sizes lived together in the wet places. Little floating algæ, hardly visible to the eye, low sedgelike forms, and even large trees were present. But there was this difference: the plants belonged more largely to the lower branches of the vegetable kingdom. Neither the cypress nor the mangrove, nor even the

tamarack and rushes, were in existence then. The prevalent plants were the seed ferns (Fig. 403) with some true ferns and other pteridophytes (see p. 293). They were free to occupy all the stations in life now held by the higher seed plants. Some were low herbs, like our modern ferns, while many had developed woody trunks with bark, and these rivaled our present day trees in stature. The numerous stumps and fallen logs which have been found embedded in the coal show that extensive forests of these trees (Fig. 404) were common in both the United States and Europe, as well as in the tropics. The graceful fronds which crowned the palmlike trees may often be found matted between layers of shale, where they have been preserved as in a botanist's press. We can gain a fair idea of the aspect of the Carboniferous forests by comparing the tree ferns which still inhabit New Zealand and Australia.

FIG. 403. — Leaflet of a seed fern from the Coal Measures of Pennsylvania.

With the seed ferns were mingled dense thickets of reeds, resembling our familiar horsetail grass (*Equisetum*). Many reached the size and perhaps the strength of the tall bamboo of Asia, although their modern descendants are of lowly stature.

Probably the largest trees of the period were the so-called "scale trees" (*Lepidodendron* and others). Unlike the preceding forms, the trunks branched as in our familiar elms, and instead of broad, feathery fronds their leaves were short and stiff, and were attached closely to the trunk and branches. The nearest living relative of the Lepidodendron is the trailing *club moss* (which is not a true moss at all), — one of the frailest little herbs of our modern forests.

Higher plants appear. — Thus far all the coal plants which have been mentioned have been members of the Pteridophyte

group or of that transitional class which we have called the seed ferns (p. 293). There is still no evidence of the existence of the plants with incased seeds and prominent flowers, but

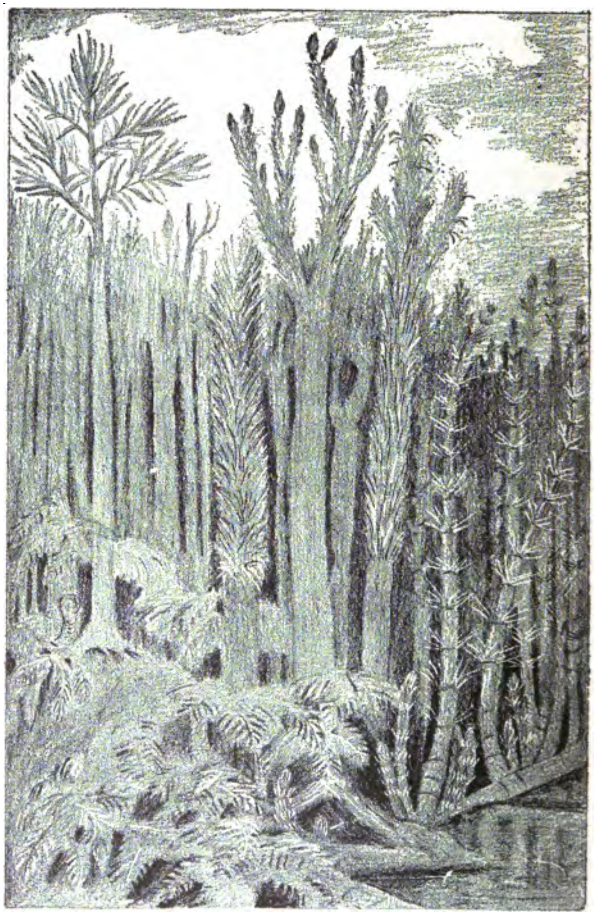

FIG. 404. — Ideal view of the trees in a Carboniferous swamp. The large cone-bearing tree in the center is the *scale tree* (Lepidodendron). On the right are gigantic horsetail reeds and on the left Cordaites, one of the earliest Gymnosperms. (After Horsfall.)

the gymnosperms were represented in the Pennsylvanian forests by *Cordaites*, a tree which combined many of the characteristics of the conifers and the palmlike cycads. They had long sword-shaped leaves and appear to belong to a distinctly higher level of development than any of the fernlike plants.

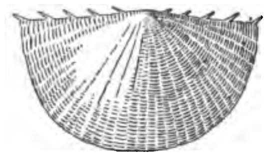

FIG. 405. — A small brachiopod (Chonetes) common in the later Paleozoic rocks.

Land animals diversified. — In older systems of rocks the remains of land animals have been found only rarely. In the Pennsylvanian, however, with its well-preserved plants, the finding of many air-breathing animals should be expected.

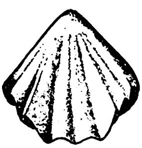

FIG. 406. — A small brachiopod (Pugnax) with sharply folded shell.

Among the arthropods, a variety of insects (Fig. 408), scorpions, centipedes, and spiders testifies to the wide diversification through which the group had passed in the periods before. As yet, however, the bees, butterflies, and other highly specialized insects had not appeared, — a fact which gains added interest from the reflection that the flowers on which these animals now depend were likewise yet to come.

FIG. 407. — A Pennsylvanian scallop shell (Aviculopecten).

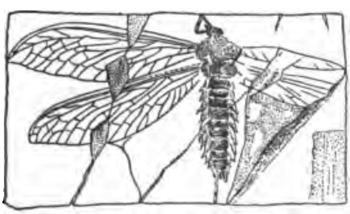

FIG. 408. — A large winged insect from the Coal Measures of France.

Amphibians take the lead. — In the Mississippian period amphibians are known to have been present. Far more abundant remains of them are found in the coal-bearing rocks which followed. Nearly all appear to have been like the salamanders in form, but many

of them had more substantial bony frames and were of larger size (Fig. 409). Certain degenerate types had lost the use of the limbs and doubtless adopted the habits of snakes.

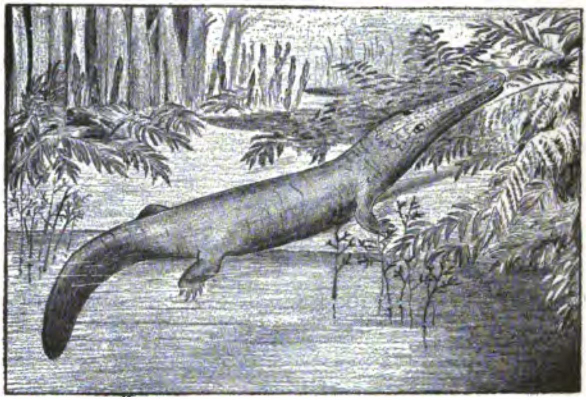

FIG. 409. — A large amphibian of crocodile-like form and habits, as it probably appeared in life.

First appearance of the reptiles. — Recently the bones of true reptiles have been discovered in the Coal Measures of Illinois and Pennsylvania. Not until the next period, however, does the class come into prominence, and so the discussion of them is deferred until that Chapter is reached.

Climate of the Pennsylvanian. — The abundance of vegetation in the coal swamps has been thought to indicate that North America and Europe were covered with tropical jungles in which the growth of plants was luxuriantly rapid. This would imply a climate warmer than that of the present, and perhaps moister.

By others, however, it is pointed out that the largest accumulations of peat are now being formed in cool regions, such as Canada and northern Europe. Singularly enough, the microscopic structure of the leaves of the coal trees is much more like that of our northern conifers and other hardy plants than like the delicate and thin-skinned leaves prevalent in

tropical jungles. Thick bark is another feature shared by the coal trees and those of our cooler countries to-day. It seems not improbable, therefore, that the climate under which many of the coal marshes flourished was more like that of Canada than of Florida or the Amazon.

Great length of the period. — While it is not possible to calculate exactly the duration of geologic periods, some rough estimates made for the Pennsylvanian are of interest. For the growth of the vegetation which made the coal seams in a single locality 1,000,000 to 2,500,000 years would seem to be required, and, for the sediments in which they are interbedded, at least as much more. It is therefore possible that 5,000,000 years were included in this single period.

Questions

1. In Pennsylvania there are thick beds of conglomerate and sandstone which contain no fossil shells, but an abundance of plant leaves in certain layers. Can you suggest the origin of these rocks?

2. The sandstone which lies at the base of the Coal Measures in many parts of this country and Europe is sometimes called the *millstone grit.* Can you suggest why this name was given it?

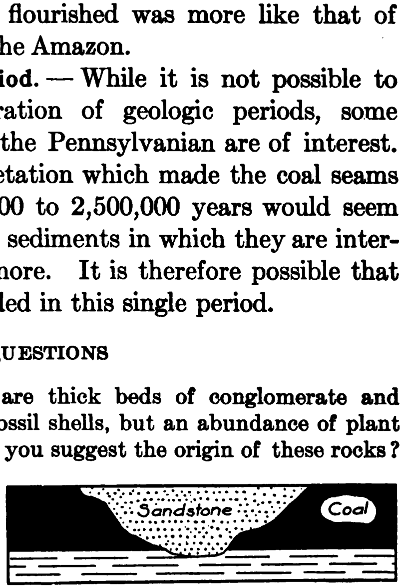

Fig. 410. — A sandstone "cut out" in a coal seam.

3. The accompanying cross section (Fig. 410) shows a narrow, winding bed of sandstone lying in a coal seam. Such things are known to the miners as "cut outs." How may such a feature have been produced?

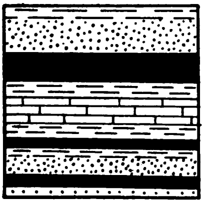

Fig. 411. — Section from Ohio Coal Measures.

4. Tell all the events and changes which you find recorded by the accompanying section taken from the Coal Measures of Ohio (Fig. 411).

5. Coal seams are often broken by faults. If in following a certain coal seam in a mine, you should encounter such a fault, how could you tell whether to hunt for the lost continuation of the bed at a higher or lower level?

6. The Pennsylvanian strata are the latest widespread Paleozoic

deposits in eastern United States. Why should their outcrops, as shown in the map (Fig. 401), be so different in shape from those of the Cambrian system?

7. In Rhode Island the coal is very hard and graphitic. From this fact what do you suspect with reference to the structure of the Coal Measures in that district?

8. From which variety of coal could illuminating gas be made to the best advantage, and why?

9. Of the mineral products which you have studied thus far, which most resembles coal in method of occurrence, — iron, copper, or zinc?

10. Iron ore is not infrequently deposited in bogs at the present time. That being true, in what part of the United States might such ore be expected in formations of Pennsylvanian age?

CHAPTER XIX

THE PERMIAN PERIOD

A transition period. — The Permian marks the transition from the Paleozoic era to the Mesozoic. In eastern United States the Permian rocks are a mere continuation of the Pennsylvanian system, while in the Rocky Mountains it is often impossible to separate Permian strata from those of the Triassic period. Only locally are the systems sharply marked off from each other.

Emergence of the eastern region. — Throughout the Permian, the interior sea was slowly being withdrawn. The deposition of the Coal Measures continued on into the early Permian in the Ohio Valley. Some of the sediments were laid down in rivers or fresh-water lakes, and contain abundant leaves of plants. Later in the period the region seems to have been drained, leaving a broad lowland which was only feebly eroded.

The sea lingers in the Southwest. — In the southern part of the tract which we now call the Great Plains the sea lingered somewhat later. Shales, sandstones, and limestones quietly accumulated in Texas, and perhaps in Kansas.

The red beds. — The later Permian rocks of northern Texas, however, tell of very different conditions; they are reddish shales, with layers of gypsum and rock salt. Evidently the sea had by that time receded still farther, leaving a desert region in western United States, with saline lakes in the depressions. In Colorado and some other places the formation of these red beds began during the Pennsylvanian and continued on into the Triassic period, indicating that the arid climate was of long duration.

Expansion of Permian lands. — The gradual withdrawal of the epicontinental sea eventually left almost all of the continental platform dry land. On studying other countries we find evidence that there, likewise, the land was more extensive than at any other period in the Paleozoic era. The Permian was everywhere a time of expanded continents. To explain such a general withdrawal of the seas the suggestion has been made that the deep ocean basins sank slightly, thus leaving the continents relatively higher than before. So widespread and radical a change marks this as one of the critical periods of geologic history.

The Appalachian trough. — Throughout the Paleozoic era, the thickest layers of sediments had been laid down in the interior sea just west of the old Appalachian land, from New England to Alabama, and even across to Oklahoma. This curved belt had been a subsiding trough, sinking perhaps because of the weight of sediments which were constantly loaded upon it. Much of the time the sinking just kept pace with the deposition of sediment, so that thousands of feet of strata were formed in relatively shallow sea water, as we now learn from the presence of such things as coral reefs. At other times, the subsidence was more rapid, and deeper water prevailed, or on the other hand was of a halting nature and allowed the coastal rivers to build out the seashore with alluvial deposits. Finally, in the Permian, the sinking and the sedimentation ceased, and the process was reversed into a slow emergence. The sediments deposited in this trough had then reached a thickness much greater than that of the corresponding strata in the Mississippi Basin.

Crumpling of the east flank of the continent. Near the close of the Permian, whether as a result of a sinking in the Atlantic basin, or from some other cause, the east side of North America was subjected to powerful horizontal compression. The Appalachian trough was a weak zone in the crust, just as the bend in a crooked stick determines the point at which it will break when pressure is applied at

the ends. From Newfoundland to Alabama and even into Oklahoma the rocks were thus crumpled. The rocks of the old Appalachian land had been folded more than once before, and so the Permian deformation added little to the com-

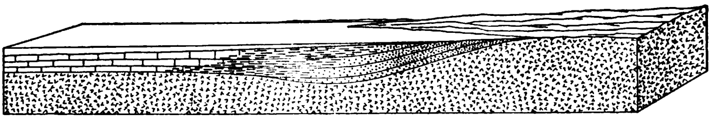

Fig. 412. — An ideal representation of the west coast of Appalachia, during the Paleozoic era. The ancient rocks on the east are being eroded, and the sediments laid down in the sea gradually become finer westward. (Modified after Willis.)

plexity of their structure. The Paleozoic rocks in the great trough, however, were now folded for the first time (Figs. 412 and 413). In Pennsylvania, the strata were bent into a series of open anticlines and synclines (Fig. 46). Farther

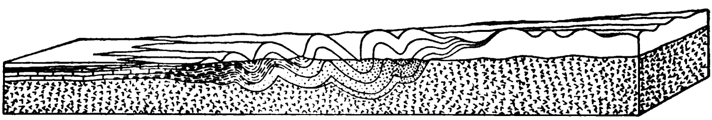

Fig. 413. — The same, after folding of the Paleozoic sediments. The unshaded portion shows the folds restored as they might have been if they had not been affected by erosion. (Modified after Willis.)

south, where deformation was greater, the folds were compressed and overturned westward (Fig. 47). Here and there the stiff limestone and quartzite formations were broken and thrust over the adjacent rocks (Fig. 414). At the same

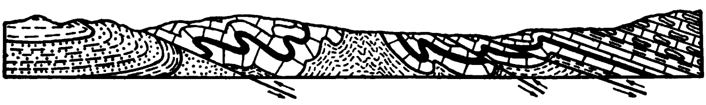

Fig. 414. — Closely folded strata in the southern part of the Appalachian mountains. (*U.S. Geol. Surv.*)

time the soft shales were crumpled and crushed beneath the stronger beds. So numerous are these overthrusts in some districts that the original folds cannot now be reconstructed.

Folding a slow process. — It is probable that the folding was accomplished very slowly, as are the larger earth movements of the present time. The anticlines probably rose so gradually that the decay of the rocks and the work of streams partially kept pace with the growth, so that the young mountains were at all times ragged and gashed with valleys. This is true of growing mountains to-day, such as the Coast Range of California and the St. Elias chain in Alaska, and it is safe to judge the Permian by the present. Even the great thrust faults, along which massive limestones have been pushed several miles over younger beds, were doubtless made by a succession of slippings, each advancing not more than a few feet, and each slip separated from the next one perhaps by months or years of time. While recognizing, however, that the folding and the uplift were very slow, we may well imagine the first Appalachian and Ouachita (Oklahoma) Mountains as a series of lofty, rugged ranges comparable to the Alps, or to the modern Pacific ranges in North America.

Effects of expanding the continents. — The widespread emergence of the continents into dry land must have produced important changes, not only in the geography of the period, but in the conditions of life for plants and animals, and even in the condition of the atmosphere and in the climate. It will be best to inquire into these matters separately.

Adversities inflicted on the sea life. — During the Paleozoic era the shallow epicontinental seas had harbored abundant marine animals and plants. With the exclusion of these broad sheets of water from the continents the home of such forms of life was much reduced in size. It would be entirely natural to expect that as a result the competition for a living would become much keener, and that many of the forms less able to adapt themselves to the new conditions would be exterminated. This may be the explanation of the well-known fact that very few of the distinctly Paleozoic fossils pass on into the Triassic system. Few of the large groups entirely disappeared, although some were much diminished,

while others, such as the corals, were largely reorganized on new plans. The change is seemingly one of the most abrupt and profound in all the geologic record. Yet in northern India and California, where the Permian seas lingered on into the Triassic, the change in the fossils is gradual and no sharp dividing line can be drawn.

More ample opportunities for the land life. — The very changes which restricted the habitation of the corals, mollusks, and their kin gave wider room to the denizens of the land. A great abundance and variety of plants and insects were already present. The salamanderlike types of amphibians were even more numerous and better constructed than in the Pennsylvanian. In fact, they were never afterward as prominent as at this time. Amphibians nowadays are small creatures, and most of them have soft bodies; but some of the Permian types were large and were more comparable to reptiles like the crocodiles of to-day with their bony-plated heads, powerful muscles, and formidable array of teeth.

Reptiles gain the ascendancy. — It was left for the true reptiles, however, to gain supremacy among the land animals in the Permian period, in spite of their amphibian rivals. When any group first appears in geologic history, it is apt to be represented by closely related kinds unlike those which live to-day. These are known as *generalized types*, because they combine vaguely in one animal the characteristics of several later kinds. Thus in the Permian there was one kind of reptile which resembled in some respects the crocodiles, the lizards, and other types now extinct, and yet cannot be classed with any one of these groups more than with the others. Later, these generalized types branched out into the distinct forms now recognized. These will be described in connection with a later period.

Prevalence of arid climates. — The abundance of salt and gypsum beds in the Permian strata of many countries has already been mentioned as indicative of desert conditions. Deserts are, of course, only possible on land, and to-day they

are especially well developed in the interior regions of large continents, for example, in central Asia. Wide extension of lands, as in the Permian, therefore favors the making of deserts in appropriate places.

Glacial conditions in the tropics. — While considering the Permian climate we must not fail to note what is easily the most remarkable fact now known about the period. Associated with rocks of Permian age layers of glacial till have been found lying upon scratched and grooved surfaces of older rocks. These glacial beds have not been discovered in the polar regions, as we might confidently expect, but in India, South Africa, South America, and Australia; that is to say, near and even within the tropics. Nor are we to suppose that glaciers were confined to lofty mountains. The limestones and shales with which some of the layers of till are associated show that they were deposited near or even below sea level.

The existence of glaciers over so wide an expanse of the earth's surface and even within the tropics themselves points to most unusual climatic conditions. We may well believe that they indicate a colder climate than now over much of the globe; but mere cold does not account for the strange distribution of the glaciers, and a satisfactory explanation of all the facts is still lacking.

Summary of the Paleozoic Era

Geographic conditions. — From the Cambrian to the Permian, the more persistent lands were in eastern Canada and southeastern United States. The central and western parts of the continent were repeatedly submerged by a relatively shallow sea. As stated on a previous page, the copious supply of detritus from the Appalachian land built up the thickest Paleozoic formations along the eastern border of the interior sea, while in the middle of the continent sedimentation went on more slowly.

In the far West, the Colorado region and parts of the Pacific

slope were occasionally out of water, — although there is little evidence that they were as mountainous as now. Where the Great Basin now is, the sea was especially long-lived, and thousands of feet of varying marine sediments were there laid down.

On the whole, the seas overlapped the continent more in the early than in the later part of the era.

Throughout the Paleozoic periods volcanic activity was confined almost entirely to the Pacific side of North America, much as in recent times. In Europe, however, most of the volcanoes were near the Atlantic. They were particularly numerous at times in the British Isles. (How does this compare with modern conditions?)

Climatic conditions. — The climates of the Paleozoic periods have left only a scanty record. That there were deserts in several countries at various times is proven by such saline deposits as those of New York and Michigan; and that moist conditions prevailed at other times is indicated by the coal beds. It was formerly supposed that the earth was hotter in Paleozoic times than now, but Cambrian and Permian glacial deposits in regions which are now semi-tropical seem to preclude this view. Of the distribution of the climatic zones we know almost nothing. We can infer their existence only because as long as the earth is round, and the surface part receives its heat from the sun, such zones must be present.

Development of plants and animals. — In reviewing the progress of the living things we see many noteworthy changes in the course of the Paleozoic era. The early periods were dominated by the invertebrated animals. One by one, new groups made their appearance; and of these, some, like the trilobites, passed their prime and slowly dwindled to extinction, while others merely retired to a subordinate position in the scale of life.

In the later periods, fishes and amphibians successively came to the front, proved themselves more powerful than the

invertebrates which preceded them, and in turn yielded partially to the reptiles, which began their rise near the close of the era.

Of the evolution of the plants we know much less; but it is clear that the ferns and some of the gymnosperms were the prevalent types in the later Paleozoic periods. The higher groups were still to be evolved.

QUESTIONS

1. Is it necessary to assume that salt lakes are detached parts of the ocean? Can fresh lakes ever become salt, and if so, how?

2. Can you suggest a reason why desert sandstones like some of those in the Permian system are usually cross bedded?

3. In Germany a single bed of salt in the Permian system is said to be more than four thousand feet thick. What does this indicate?

4. What is the significance of the Permian system in India with reference to Laplace's theory of the origin of the earth?

FIG. 415. — Glacial markings on a rock surface.

5. Although in Australia the center of Permian glaciation is not known, and neither surface moraines nor drumlins have been identified, the direction of glacial movement has been determined. Can you suggest how from a single striated surface of rock (such as represented in Fig. 415) one may learn whether the ice was moving toward the left or right?

6. It is often said that coal has been formed in tropical jungles. What is the significance of the coal beds which lie between sheets of glacial till in Australia?

CHAPTER XX

THE TRIASSIC PERIOD

Transition from Paleozoic to Mesozoic. — The Permian period fades into the Triassic so gradually that a dividing line cannot always be drawn between them. In eastern United States, it is true, great geographic changes had taken place, and the crumpling of the Appalachian sediments had produced ranges of mountains where there had been a coastal plain before; but the rest of the continent remained much as in the Permian period.

Deserts continue in the West. — In the Triassic, as in the Permian, red sediments were deposited where the Great Plains and Rocky Mountains now stand. Beds of gypsum, the relics of salt lakes, point to the prevalence of desert conditions, much as in Nevada and Utah to-day. Needless to say, the remains of living things are very rare in the red beds. It is probable that much of the West was an inhospitable place for both plants and animals, except such hardy forms as were fitted to live in an arid land.[1]

Marine strata on the Pacific slope. — Marine rocks of Triassic age are found only on the western border of the continent, and in but few places even there. From this we may infer that the seas which had been drawn off from the continental platform during the Permian were very slow in creeping back upon it. The Pacific is the only ocean known to have encroached upon the North American land during the period. Its shore line lay somewhat farther east than now, especially in British Columbia and Alaska. In the United States it reached Idaho and Nevada. Off this coast thick

[1] It may be noted, in passing, that desert conditions were prevalent also in western Europe at this time, as they had been in the Permian period.

banks of mud and ooze accumulated. In consequence of compression at a later time, the sediments are now folded slates and schists.

Erosion of the new Appalachian Mountains. — No surely marine beds of Triassic age are exposed in the eastern part of the continent. The land probably extended out even beyond the present Atlantic shore.

The growth of the young Appalachian Mountains seems not to have ceased entirely in the Triassic period. As the Paleozoic rocks were folded, the eroded surface of old Appalachia was likewise warped, and, in the broad downwarps, streams continually spread the abundant sand and silt which they were removing from the mountains. The deposits on the low slopes and bottoms of these basins eventually reached a thickness of thousands of feet; and, as is common among rapidly accumulating sediments, the particles were not well assorted. Alternations of sandstone and shale of varying colors are characteristic of the *Newark formation*, as these beds are called. Red is the predominating color.

Locally, as in southern Virginia, the Triassic rocks include a few beds of coal, which bespeak the growth of marshes in the low grounds. The fact that these marshes existed probably means that the climate of the Atlantic seaboard was less arid than that of the West.

Volcanic eruptions in the Atlantic slope. — About the time the Newark sediments were being laid down, eruptions of basaltic lava occurred in the same district. Some of the basalt sheets rise obliquely through the strata, thus proving that they were squeezed into the rocks as intrusions. Others have cindery surfaces and are overlain by sandstones which are not altered at the contact with the lava. Here, evidently, the flows were poured out upon the surface and afterwards buried beneath sediments.

Being harder than the sedimentary strata, the lava sheets have been left as ridges in the subsequent wasting of the surface. The palisades of the Hudson and such heights as

Mt. Holyoke in Massachusetts are merely the outcropping edges of hard Triassic lava sheets, formed during this epoch of volcanic activity, — the last in the history of the eastern portion of North America.

Life of the Triassic

New aspect of the marine invertebrates. — Although the lower animals of the Triassic seas resemble the Paleozoic types in many ways, the differences are nevertheless very distinct. Not only had some of the Paleozoic groups, such as the trilobites, wholly disappeared, but others, as the brachiopods (Fig. 416), had been relegated to an inferior station.

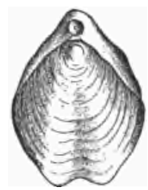

Fig. 416. — A Triassic brachiopod (Terebratula). The majority of Mesozoic brachiopods have this general form.

The mollusks became the most abundant and conspicuous of the shelled animals, and among them the group of coiled cephalopods had a remarkable development during the Triassic and later Mesozoic periods. From the simple types with straight sutures, they had advanced later in the Paleozoic to the possession of lobed or wavy sutures. In the Mesozoic era the folding of the partitions became most intricate (Figs. 418 and 419), producing equally complicated suture patterns.

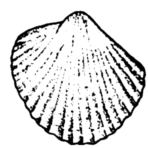

Fig. 417. — A small pelecypod from the Triassic limestone of Europe.

Fig. 418. — An ammonite with part of the outer shell removed to show the complexly folded sutures.

Reptiles overreach the amphibians. — The brief supremacy of the clumsy amphibians had now

passed. Large alligatorlike forms of powerful build were still common in the Triassic marshes, but after this period the class was represented only by smaller soft-bodied types, such as frogs and salamanders.

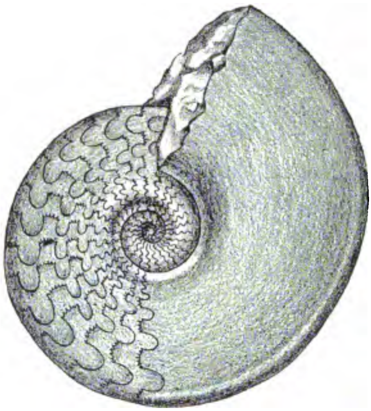

FIG. 419. — One of the simpler ammonites (Ceratites) showing the moderately folded sutures.

The reptiles were the class in power. — The bones of many reptiles have been found in the Triassic rocks, and the existence of others is made known to us by the host of footprints (Fig. 420) which they left upon the muddy flats along the slack rivers and bays, as in the valley of the Connecticut River. The mud has since hardened into stone, but without effacing the footprints. Some of these tracks show the marks of three toes, and were at first very naturally mistaken for those of birds.

FIG. 420. — Tracks of three-toed reptiles found in the Triassic sandstone of the Connecticut Valley. (After Hitchcock.)

The reptiles adopt many rôles of life.—There seems to be no doubt that the ancestors of the early reptiles were the amphibians. We may think of them, then, as originally inhabitants of marshes and inland bodies of water. Reptiles adapted for such a partially aquatic life were rather common in both the Permian and Triassic periods, as their fossil remains attest.

The terrestrial type becomes prominent. — Some of the reptiles came to spend more and more time on land, and eventually became fitted for living wholly under such conditions. Some walked on all fours, as do our modern cattle and many other mammals, but the more agile varieties apparently were leapers, using their powerful hind legs and stout tails after the manner of the kangaroo. The majority of these swifter forms seem to have preyed upon other animals, and for this purpose their teeth were sharp and strong. They played the rôle of our modern beasts of prey, such as the tiger and the wolf, although in a manner no doubt peculiar to themselves.

Reptiles find a place in the sea. — The tempting source of food which the fishes and mollusks of the sea presented was early appropriated by other branches of the reptilian stem. Two main types were represented in the Triassic period. Of these the *Plesiosaurs* were large, flattened saurians with long, slender necks and short heads. Their legs eventually became mere paddles like those of the modern sea turtles. The suspicion that they fed partly upon mollusks, for which they probably delved in the shallows with their long necks, is strengthened by the finding within their bodies of smooth pebbles, thought to be gizzard-stones used to pulverize the food swallowed.

Of all the reptiles none were better fitted for living exclusively in the open sea than the *Ichthyosaurs* (fish-reptiles). They had acquired the form of fishes themselves (Fig. 421), with the long powerful tail fin, the short neck, and long jaws set with sharp teeth. These animals seem to have been almost exclusively fish eaters. Most aquatic reptiles, for example the turtles, lay their eggs in sand along the shore;

but the ichthyosaur, having lost the power of resorting to the shore to lay its eggs, was in the habit of bringing forth its young alive, as is proved by the interesting find of five little ichthyosaur skeletons undamaged within the skeleton of one of these reptiles.

FIG. 421. — A family of fish reptiles (Ichthyosaurus). (Painted by C. R. Knight, under the direction of Professor H. F. Osborn. Copyright by *Amer. Mus. of Nat. Hist.*)

Mammals make a feeble beginning. — Were it not for the overwhelming predominance to which the mammals afterwards attained, their first appearance would be scarcely worth mentioning. In the Triassic rocks a few little bones have been found which seem to be those of primitive mammals.

They were as small and insignificant as the moles of to-day. The most distinguishing thing about them is that their teeth were differentiated into incisors, canines, and molars, as in mammals, while almost all reptiles have merely pointed teeth much alike throughout the jaw. The derivation of mammals from some of the Permian land reptiles is now the most favored view.

FIG. 422. — A living Mexican cycad. (Photograph by C. J. Chamberlain.)

Conifers and cycads make the forests. — A change in the plants which had been in progress during the Permian was clearly defined in the early Mesozoic periods. The great ferns and allied trees of the Carboniferous forests were supplanted by a higher group (gymnosperms) containing the conifers and the palmlike trees called *cycads* (Fig. 422).

Ferns continued to be common, but there were more of the small varieties, like those now growing in our forests, than of the tree ferns. The woodlands of the Triassic times doubtless had a somber aspect not unlike that of our pine forests to-day. Nor is it surprising that the purely vegetarian land animals were then so little developed, when we consider that the tough, fibrous leaves of palms and the resinous needles of pines and similar plants are among the least palatable foods for our modern cattle and wild animals. The introduction of these higher animals seems to have awaited the evolution of the flowering plants, particularly the grasses.

Questions

1. In the Humboldt Mountains of Nevada the marine Triassic rocks rest on metamorphosed pre-Cambrian beds. What different explanations may be offered?

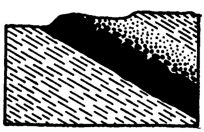

Fig. 423. — Conglomerate with lava pebbles resting upon a sheet of lava.

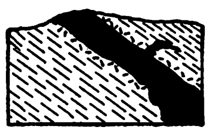

Fig. 424. — Sheet of lava with secondary minerals in the adjacent shale.

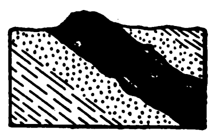

Fig. 425. — A sheet of lava with included pieces of the adjacent rock.

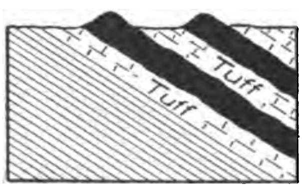

Fig. 426. — Sheets of lava interbedded with layers of tuff.

2. In the diagrams (Figs. 423–426), which are the intrusive and which are the extrusive lava sheets, and how are the facts known?

3. Small bodies of copper ore have been found in the Newark rocks. What do you suspect as to their origin?

4. Some of the sandstones in the Newark series contain abundant grains of feldspar and flakes of mica. How do these rocks differ from ordinary sandstone? Can you suggest the conditions under which the two different varieties are made?

5. What kinds of fossils would you expect to find in the Newark series, and what about their abundance? Why?

CHAPTER XXI

THE JURASSIC PERIOD

Land in eastern North America. Rocks which were made during the Jurassic period are not extensively exposed in the United States, and for the most part they are less well known than those of other periods. In the eastern half of the country no rocks which are surely[1] of this age have been discovered. From this circumstance it seems probable that the eastern part of the continent was largely out of water, and that the erosion of the Appalachian region was still in progress. After the deposition of the Newark sediments during the later part of the Triassic period, the eastern border of the continent was slightly warped. As a result, the Triassic rocks are now tilted, to the east in New England, and to the west in New Jersey and southward. During the same disturbance the rocks were broken by many normal faults which, in some instances, repeat the interbedded sheets of lava (Figs. 427 and 428).

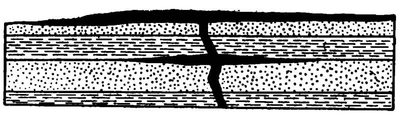

FIG. 427. — Triassic sediments in Connecticut with a surface flow and intrusions of lava, as they may be supposed to have existed before faulting.

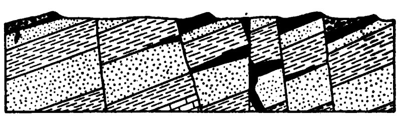

FIG. 428. — The same, complicated by several normal faults and eroded to a peneplain.

Temporary inundation of the Northwest. — Little is known of the events of Jurassic times in the great interior of the

[1] It has been suggested that some doubtful fresh-water deposits along the Potomac River in Maryland are of Jurassic age, but it is equally probable that they are Comanchean (Lower Cretaceous).

United States. In the West only barren sands and clays, such as accumulate on land, and probably under conditions of dry climate, seem to have been deposited in the earlier part of the period. Later a broad tract extending from Alaska south to Wyoming and Utah subsided enough to let in an arm of the sea. That this sea was shallow is indicated by the character of the sediments, which are shales and sandstones, with occasional beds of limestone. The fossils in the limestones are not only the remains of animals which lived in the ocean, thus proving that this was the water of the sea and not of a large lake, but they were most nearly related to the animals which lived at the same time on the coast of Alaska, and even in Siberia.[1] Their affinities with the Californian types are much less close. From this we may infer that the sea came in from the far north rather than from the west (Fig. 432). This inundation of the Northwest during the late Jurassic was of short duration only. At the close of the period, changes of level,

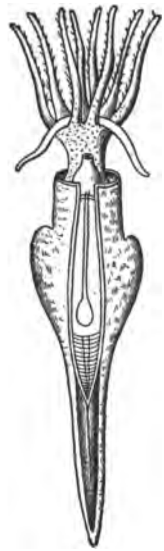

FIG. 429. — Probable appearance and structure of a common Jurassic mollusk (Belemnites) allied to the modern cuttlefish. The shell is the shaded portion below and is the only part usually preserved. (After Pictet.)

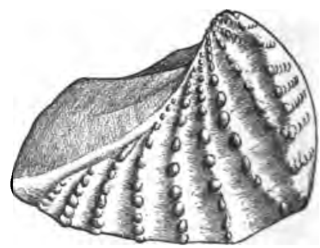

FIG. 430. — A large and oddly ornamented pelecypod (Trigonia) of the Jurassic period.

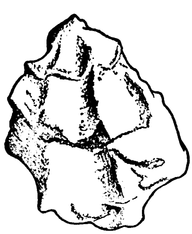

FIG. 431. — A Jurassic oyster shell (Ostrea).

[1] At this time Siberia and Russia were largely submerged by an expansion of the Arctic Ocean, and broad bays spread southward from this into central and western Europe joining the ancestral Mediterranean Sea, which was much larger then than now.

FIG. 432. — Geography of North America as it is supposed to have been in late Jurassic time. Dotted pattern represents sediments on land.

the reverse of those which had brought in the sea, again excluded it. In neither case were the strata disturbed, and where there is any unconformity above the marine beds it is barely detectable.

Marine deposits along the Pacific slope. — On the Pacific coast there was a very different state of affairs. Throughout

the period sediments had been accumulating along the margin of the ocean, which at that time spread eastward as far as Nevada. Probably deposition had been going on along this coast through several of the preceding periods also. By the close of the Jurassic period the result was a very thick body of marine sediments, chiefly shales and sandstones, which had been laid down in shallow water, and, as the general fineness of the material testifies, near a coast which was not rugged.

Crumpling on the Pacific border. — At the end of the period this long cycle of deposition was interrupted by one of those intense crumplings of the earth's crust, which at intervals throughout geologic history have disturbed first one locality and then another. By lateral compression, the driving force of which seems to have originated in the deep basin of the adjacent Pacific Ocean, the shales and sandstones were closely folded so that the beds now stand on edge. At about the same time, great quantities of igneous rock, especially granite, welled up into the folded mass, and solidified in the form of stocks and huge batholiths. On the borders of these intrusions, the sedimentary beds were changed into schists and other metamorphic rocks. Even at a distance from the igneous masses, the intense pressure exerted was sufficient to convert the deeply buried shales into hard slates, and, in some cases, to metamorphose the rocks even more severely. The result of this series of disturbances was doubtless a wrinkling and cracking of the surface of the land parallel to the Pacific through California and probably as far north as Alaska. Mountain ranges were raised on the site of what had previously been a shallow sea. Even as they were elevated, these mountains were being gradually dissected by running water and the other agencies of degradation, just as the rising Sierras to-day are being sculptured. In their youth, we may well suppose that these early ancestors of the present Sierra and other Pacific ranges were lofty and rugged mountains. They have since, however, been worn down and have

totally disappeared, the mountains which now occupy the same territory having been made at a much more recent date by the reëlevation of the same strip.

LIFE OF THE JURASSIC

Culmination of the reptiles. — In the Jurassic period the reptiles, which had been rising into prominence since the Permian, reached the climax of their career. Type after type had made its appearance, until by this time the animals of the reptilian class had assumed most of the rôles and taken

FIG. 433. — A Jurassic dinosaur (Stegosaurus), as it may have appeared in life. (Painted by C. R. Knight, under the direction of Professor H. F. Osborn. Copyright by *Amer. Mus. of Nat. Hist.*)

possession of most of the habitats which were open to them. The mammals and the birds were then in a very primitive condition, and occupied an insignificant place. The stations which they have since acquired were then held by the reptiles. The few rather small and unpretentious reptiles which now remain, — for example, the snakes, lizards, and turtles, — give but a faint conception of the saurian class in its prime. In the Jurassic, there were also large and ponderous reptiles (Fig. 433),

which more or less resembled the great modern pachyderms such as the elephant and the rhinoceros. They fed upon vegetation, and in spite of their bulk and the formidable array of bony plates, scales, and spines with which many of them were protected, they were probably neither ferocious nor dangerous. There were also smaller and more active reptiles (Fig. 434), which, like the tigers, lions, and other flesh-eating mammals of the present, preyed upon the more sluggish varieties that fed on vegetation.

FIG. 434. — Carnivorous dinosaurs (Allosaurus) of the Jurassic period. (Restored by C. R. Knight, under the direction of Professor Edward D. Cope.)

Besides the land reptiles, there were batlike forms which had developed the power of flight almost as fully as did some of the birds in later times. These *pterosaurs* (Fig. 435), or flying dragons, as they are sometimes called, had hollow bones and other characteristics which are now peculiar to the birds. One of them had a spread of wings of more than twenty feet, — nearly twice that of the largest living bird — but the majority were much smaller.

FIG. 435. — The largest of the pterosaurs. A Cretaceous species. (Painted by C. R. Knight, under the direction of Professor H. F. Osborn. Copyright by *Amer. Mus. of Nat. Hist.*)

In the shallow waters along the seacoasts and in the marshes of the rivers and inland bodies of water, other reptiles which had adopted an aquatic mode of life were abundant. Some, like the turtles and crocodiles of to-day, divided their time between the water and the shores, and were provided with legs fairly well adapted for either situation; while others, as described in the last Chapter, had become adapted for swimming only. Their feet had been changed into flippers not unlike those of a whale, and in the extreme examples of this adaptation, only the front pair of paddles remained. The rear pair, being apparently less useful, had gradually disappeared, as in the modern whale. In such types the loss of the rear legs was always compensated for by the development of a long and powerful tail, flattened so as to serve as an efficient propeller.

The mammals still in the background. — The birds and mammals have been casually mentioned as occupying a

subordinate place on the stage of life in the Jurassic period. The mammals had, indeed, made their appearance as early as the Triassic, but they were still very primitive and quite unlike any forms which exist to-day. Not one, the remains of which have been discovered, was much larger than a rat, and there are reasons for believing that many of them belonged to the lowly group of egg-laying mammals, which is now extinct save for the duckbill and spiny anteater of Australia.

FIG. 436. — The earliest known bird (Archæopteryx). (Modified after Hutchinson.)

The earliest of the birds. — Our first evidence of the existence of the birds comes from the Jurassic rocks of Germany. In the wonderful lithographic limestone of Bavaria several specimens, including even the feathers, have been found. They represent a bird (Fig. 436) which was so unlike the birds of to-day that, aside from the feathers and the warm blood which those feathers imply, it might with considerable justice be looked upon as a reptile rather than a bird. In its

jaws were conical teeth like those of a lizard, and its long tail had bones out to the very tip. The fingers of the front limbs (or wings) were still free and distinct, whereas in all modern birds they havė entirely grown together into a single bone, to which the feathers are attached. Its characteristics, then, are essentially intermediate between those of reptiles and of birds, and seem to indicate, with more than usual certainty, that the birds are the direct descendants of some one of the earlier reptiles.

Questions

1. The faulted lava beds of late Tertiary age in Oregon and Nevada now stand out as high mountain ranges, while those in New Jersey make very low mountains, or hills. Can you explain?
2. What does the thin shale and limestone formation of Jurassic age in northwestern United States tell us about the Rocky Mountains in that period?
3. There are many lava flows interbedded with the Jurassic shales in California, and the shales contain marine fossils. From this what do you infer as to the conditions at that time and place?
4. Under what conditions does molten lava form granite?
5. Why are granites the commonest rocks in batholiths?
6. How does it happen that many batholiths of granite are exposed at the surface to-day?
7. In what kind of a deposit should the most delicate fossil be most perfectly preserved?

CHAPTER XXII

THE COMANCHEAN PERIOD[1]

Conditions at the beginning of the period. — The opening of the Comanchean period found the continent of North America very largely out of water, the long gulf from the northwest having been excluded at the close of the preceding period. On the west coast the series of rugged mountains which had been produced by the Sierran disturbance were being eroded, and the material supplied by their decay was spread along the shores of the Pacific Ocean. The present Rocky Mountains and most of the numerous ranges of the Great Basin region were not then in existence. From the Pacific mountains to the Atlantic Ocean there were probably no prominent highlands, except some low mountains in the Carolina region and perhaps others in New England. By this time the folded ranges of the Appalachian system had been worn down to a lowland or peneplain, over which sluggish rivers meandered on their way to the Atlantic Ocean and the Gulf of Mexico, and above which a few scattered hills rose as monadnocks.

The beginning of the coastal plain. — Up to this time the coast line of eastern and southern United States appears to have been considerably farther out toward the edge of the continental shelf than now, for almost no Paleozoic or early Mesozoic rocks of marine origin have been discovered there. In the Comanchean, for the first time, sediments were laid down over a considerable part of the old Appalachian land, now represented by the Piedmont Plateau. In the broad, level flats and marshes back from the coast, deposits of sand and clay with occasional carbonaceous layers were formed.

[1] Often called the Lower Cretaceous period.

These are known locally as the *Potomac series*. Similar strata are found in the eastern Gulf states, and there, too, they are not of marine origin. In Texas and Mexico the sea spread far inland during the early part of the Comanchean period. That the submergence came on gradually and disappeared equally slowly may be readily inferred from the character of the rocks of that age. Thus the lowest beds of Comanchean age in Texas do not contain marine fossils. They are mixed sands and clays, with traces of marsh vegetation, — facts which indicate that they were laid down upon a low-lying land, perhaps in the lagoons and flats along meandering rivers. Upon these earlier strata shales and limestones are found, and the marine shells which they contain prove that they were deposited in the sea, which was then advancing northward over the land. Above the limestones, however, are more sandy beds, which indicate that the shore line was on its retreat southward, and the sea was becoming shallower, until finally Texas and neighboring regions were left dry again.

Reduction of the Pacific mountains. — On the Pacific slope a vast thickness of gravel, sand, and mud accumulated during the Comanchean period. No other evidence is needed to show that the mountains which had been upraised at the close of the Jurassic were being rapidly eroded and the products of their decay carried into the adjacent sea. Hundreds and doubtless thousands of feet of rock were carried away by these slow but incessant processes, resulting in the uncovering of even the deep-seated batholiths of granite, which had been intruded at the time of the folding.

Emergence of the continent. — Above the Comanchean strata there is almost everywhere a distinct unconformity, which tells of long-continued erosion after the sediments were deposited. In the Atlantic and Gulf coastal formations the unconformity is merely an irregular surface dividing the strata above from those below. In that region there was no notable deformation between the two epochs of deposition. On the Pacific coast, however, the unconformity is more promi-

nent, and in Mexico it is still more conspicuous, for there fault scarps which were made at the close of the Comanchean were base-leveled before the Cretaceous sediments were deposited. In Europe, also, an unconformity has been observed. From the wide distribution of these conditions, it seems probable that the sea level was drawn down at the close of the Comanchean period, and that the continents were again largely out of water.

The plants become modernized. — Up to this time the vegetable world had been represented entirely by such fossil plants as the ferns, mosses, and cycads, — plants which belong to distinctly lower groups than those with which we are now most familiar. In size and abundance they probably compared well with our modern trees, shrubs, and grasses, but they were different in structure and aspect. In the Comanchean period, for the first time, the modern flowering plants made their appearance, and in this case with a suddenness which is yet to be explained. By the end of the period they had become the most abundant of all plants in America, and later in Europe, and they have continued to hold their supremacy ever since. It is a significant fact that not long after the advent of the flowering plants came the great rise of the mammals, and also the first appearance of the higher insects, such as the butterflies, bees, and wasps. These animals are, in fact, largely dependent upon the higher types of plant life for their existence, and their rapid development may be due in no small measure to the entrance of the *Angiosperms* (p. 294).

Lesser changes among the animals. — By a somewhat slower development, the fishes likewise had reached almost their modern position by the close of the Comanchean period. The peculiar and in many respects ill-constructed fishes of the earlier periods, from the Silurian on, were gradually relegated to the background, while the modern *Teleosts* became the most abundant types, — fishes like our modern bass, salmon, and many others, which have well-developed bony skeletons.

The reptiles had by this time passed their zenith, but the discussion of their decline and the final exit of most of them from the stage of life is reserved for the next Chapter.

Questions

1. Can you suggest from Figure 437 how it may be inferred that the Appalachian Mountains were worn down to a lowland by the Comanchean period?

Fig. 437. — Generalized section of the Atlantic slope of the United States, showing the relation of the base of the Potomac sediments to the tilted Triassic beds and the folded Paleozoic strata.

2. Under what conditions might a period of emergence and land conditions not be marked in the section by an unconformity? Where in the United States at the present time are these conditions realized?
3. Can you suggest why the Comanchean system contains chalk in Texas but marble in central Mexico?
4. The Comanchean rocks of California are said to be 25,000 feet thick, while in New Jersey they are only 700 feet thick. What reasons may be suggested for this great difference?
5. Why are bees now dependent on the angiosperms?

CHAPTER XXIII

THE CRETACEOUS PERIOD[1]

Renewed inundation of the continent. — Throughout the first three periods of the Mesozoic era the seas had overspread only small portions of the United States. The areas submerged were (1) the Pacific coast in the Triassic, with the addition of the northwestern mountain region in the Jurassic, and (2) the southwest part of the Great Plains in the Comanchean.

The Cretaceous period, on the other hand, was characterized by a widespread inundation of this and most other continents. For North America, at least, it was the last time that any large part of the continent was covered by the sea.

The coastal plain submerged. — It will be recalled that along the Atlantic coast the Comanchean strata are sands and clays, which were not deposited in the sea, but more probably along rivers and marshes. A series of marine beds of Cretaceous age lies upon them, but the two are separated by a slight unconformity. The unconformity represents an interval during which the plain was land, and was subject to erosion.

The Cretaceous beds are, like the Comanchean, almost unconsolidated, but they differ in some respects from the latter. Besides clay and ordinary sand, one of the constituents of the Cretaceous, especially in New Jersey, is *greensand*, which seems to be a chemical precipitate formed in relatively shallow water.

[1] As used here, the name *Cretaceous* refers to the "Upper Cretaceous" of many writers.

Farther south in Alabama and Mississippi, the Cretaceous system includes several hundred feet of chalk or soft limestone. In the belt where this chalky formation outcrops, the soil is so good that the cotton plantations there are the richest in the South. In the same region the slave population was densest before the Civil War and the proportion of negroes is now largest.

An interior sea divides North America. — Very early in the Cretaceous period the sea which lay south of the United States began a slow advance northward over the nearly

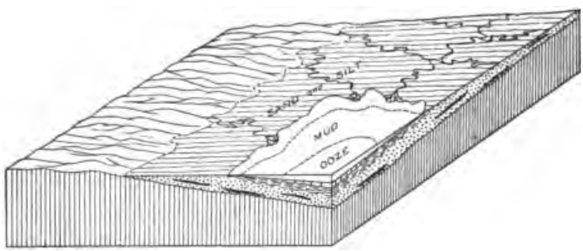

Fig. 438. — Stereogram of part of the Great Plains early in the Cretaceous period, showing the probable relations of the zones of different kinds of sediments.

level surface of the land. Along the shores of the sea there were probably marshes and lagoons such as now fringe the low coast of Texas. Still farther inland, there were broad plains over which the sluggish rivers were spreading fine sediments (Fig. 438).

As the sea advanced northward, the shore conditions must have migrated slowly in front of it, the streams constantly depositing sediment farther and farther north as the advance continued. These deposits of the alluvial plains appear to be represented in the oldest Cretaceous formation of the Great Plains region, the Dakota sandstone. In this sandstone many leaves of land plants have been found (Fig. 439). As the leaves are unworn, and are well preserved, one can hardly suppose that they were washed out to sea and

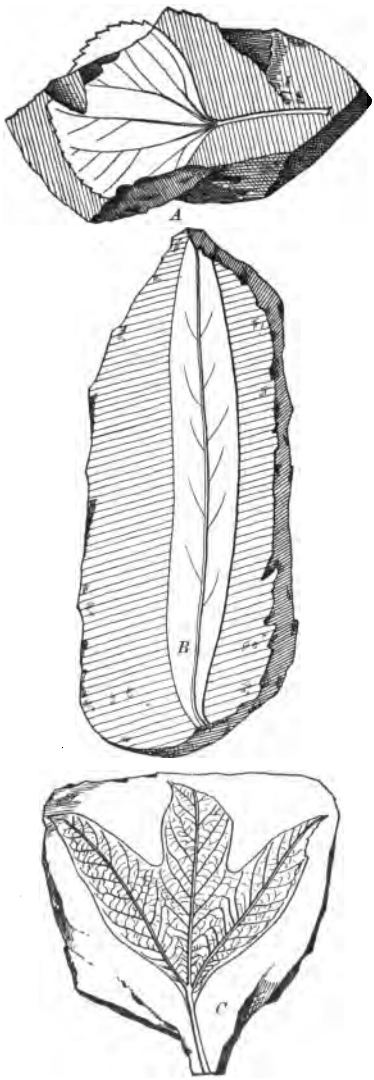

FIG. 439. — Angiosperm leaves from the Dakota sandstone. *A*, Poplar; *B*, Willow; *C*, Sassafras.

there deposited; it is more probable that they fell directly into the sandy shallows of rivers and bayous, and were in turn covered by the sands. Being a porous layer between beds of dense shale, the Dakota sandstone serves as an important reservoir for underground water, and from it many artesian wells in the northern part of the Great Plains derive their flow.

Beyond the shore line, in the open sea, very different deposits were being laid down, of course, — chiefly clays in a broad belt near the shore, and limy ooze farther out in the clear water (Fig. 440). The shells and bones of marine animals became embedded in these deposits, and are now found as fossils in the Cretaceous rocks. These two zones, in which clay and ooze were deposited respectively, likewise migrated northward as the sea advanced in that direction, until finally they had overspread the Great Plains and Rocky Mountain region, from Oklahoma and Iowa on the east to Arizona

and Utah on the west, and as far north as the Arctic Ocean. At this time, then, North America was divided into two land masses (Fig. 441): one on the east, which, being very low, furnished little but fine sediments to the

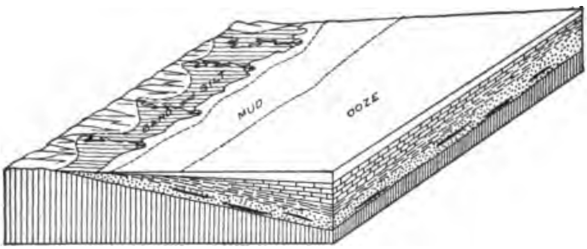

FIG. 440. — The same region as in Figure 438 near the middle of the Cretaceous period, showing the retreat of the shore and the changed positions of the zones of sediments.

interior sea; and one on the west, which was more rugged, although by no means so mountainous as the same region is to-day.

By the advance of the first zone of marine deposition spoken of above, a thick layer of clay was gradually built up over the Dakota sandstone, and this in turn was followed by the zone of calcareous ooze, which produced the chalk now found in Kansas, Nebraska, and the Dakotas. The chalk points to the existence of a clear, open sea beyond the reach of mud-laden currents. In this chalk are found not only marine shells, but the bones of large swimming reptiles, and even of birds and flying reptiles. In the latter we seem to have evidence that the winged animals of Cretaceous times were accustomed to fly far out over the sea, as gulls and albatrosses do now.

The interior sea retreats. — The duration of the interior sea was evidently long, but before the close of the Cretaceous period changes began which eventually caused its disappearance. The sediments which were being constantly swept into it around its borders helped in some degree to

fill it up, but the chief cause of its withdrawal is probably to be found in gentle changes of level, — this time the re-

FIG. 441. — Probable geography of North America near the middle of the Cretaceous period. The dotted pattern represents terrestrial deposits.

verse of those which had caused it to overspread the land. As the sea receded, the zones of sedimentation (ooze, mud, sand, and river deposits) began a slow retreat. This migra-

tion is recorded in the series of clays and sands which lie upon the chalk, and by more sands containing coal seams, which in turn are spread upon the clays. The presence of the coal seams records the passing of the shore line. The retreat of the sea seems to have been somewhat halting, however, and interrupted by occasional small advances, for marine strata are found interbedded with the coal-bearing sandstones. That the retreat was exceedingly slow, and that the land stood for a long time not far from sea level, is suggested by the thickness of the sediments which accumulated and by the number of successive coal beds in the upper part of the system. Each distinct series of beds thus made has a name of its own, the uppermost or coal-bearing series being called the *Laramie* formation. There may be as much coal in the Laramie as in the Pennsylvanian system in eastern United States, but on the average it is of poorer quality, and but little of it is anthracite.

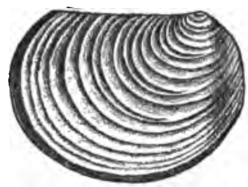

FIG. 442. — A pelecypod (Inoceramus) of the Cretaceous shales characteristic of the western plains.

FIG. 443. — A Cretaceous gastropod with curiously formed shell and beaded ornamentation.

Local deposits on the Pacific coast. — In California and northward at various points as far as Alaska, Cretaceous sandstones and shales have been recognized. They are usually separated from the Comanchean strata by an unconformity, because much of the coastal region was land for a

FIG. 444. — A Cretaceous sea urchin or echinoid, with the spines removed.

considerable interval at the close of the Comanchean period.

The Cretaceous sediments were evidently derived from the mountains which bordered the Pacific shore. These mountains were probably higher in the preceding period, but had been much reduced before Cretaceous times. The thickness of the Cretaceous sediments is correspondingly less than that of the Comanchean system. In explanation it may be suggested that the mountains had been eroded down to a subdued hilly tract before the Cretaceous period.

A period of quiet throughout the world. — We have already seen how the eastern and western portions of the continent had been reduced to lowlands, either before the Cretaceous or by the end of that period. The only notable elevations which seem to have remained in North America were certain hills and mountains along the Pacific coast and others in the Carolinas. The same condition may be traced in Europe and in Asia, where peneplains of enormous extent seem to have developed by this time. While the lands were thus low and monotonous, comparatively little sediment was being worn from them, and even that was fine mud and silt. In the flood plains of the broad river valleys, clays and silts were spread in very wide but thin layers interspersed with marsh deposits; while along seashores little except mud accumulated, and the deposition of pure lime ooze was permitted comparatively near the coast. Thus in England and France, and in many other parts of the eastern continents, the Cretaceous rocks consist largely of chalk or limestone.

Greater uniformity of climate than we now have seems to have been another characteristic of this quiet period of low lands and shallow seas, for plants much like those of the Gulf states lived also in Greenland, where snow and ice now prevail.

Conditions favor the sea animals. — The conditions of life in such a period must have been somewhat more stable

than at periods like the present, in which comparatively rapid changes have been taking place. Uniform climates permitted the migration of both animals and plants over wide stretches of the continents and of the seas. The broadly expanded shallow seas afforded a congenial field for the increase of marine life. Along with shells, corals, and other remains of sea animals, we find in the Cretaceous rocks the bones of many marine reptiles, — not only turtles like

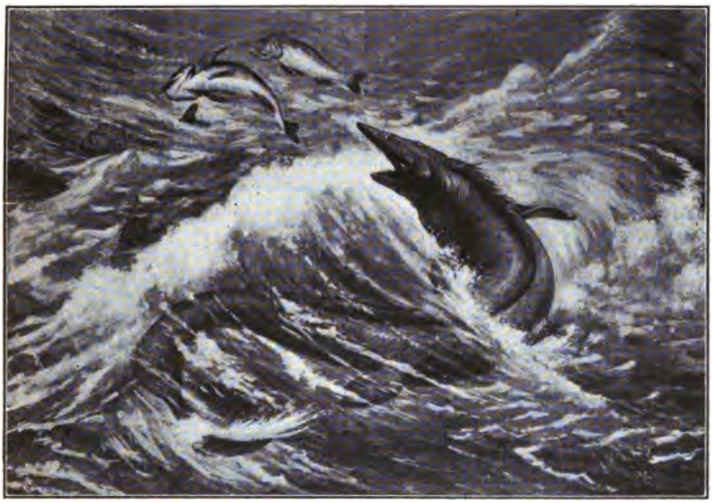

FIG. 445. — A Cretaceous mosasaur. (Painted by C. R. Knight, under the direction of Professor H. F. Osborn. Copyright by *Amer. Mus. of Nat. Hist.*)

those which now inhabit the oceans, but long, serpentlike forms in which the legs were reduced to short paddles, while the long, flattened tail served as a strong propeller (Fig. 445). The sharp teeth of these *mosasaurs* is ample evidence of their ferocious nature.

Eccentric forms of the older reptiles. — The large land-inhabiting reptiles, or *dinosaurs*, which had reached the zenith of their career in the late Jurassic, were still abundant, but had entered upon a period of eccentric diversification

such as is characteristic of the decline of many other animal groups. Like their predecessors, they were ponderous and clumsy in the extreme, and the small size of the cavities in their skulls shows how insignificant was the capacity of their brains and how little intelligence most of them possessed. Externally they took on many peculiar and apparently useless styles of ornamentation, such as the great bony plates and spines shown in Figure 433.

FIG. 446. — A Cretaceous ammonite ornamented with blunt spines. The complexity of the sutures is concealed by the shell.

The coiled shells called *ammonites* seem to have been in the same stage of their career, and likewise exhibit many peculiar forms and ornaments (Fig. 446). Some had spines, others knobs or ridges, while some showed a tendency to uncoil and revert to the straight Orthoceras type, although still keeping the highly crumpled suture lines (Fig. 447).

FIG. 447. — Fragment of a large partly uncoiled ammonite, showing remarkable complexity of the suture lines.

The birds in transition. — The birds in the Cretaceous period were far more like our modern birds than was the strange *Archæopteryx* of the Jurassic. In fact, the one characteristic which linked them closely with that ancestral form was the possession of teeth resembling those of reptiles and set in sockets or grooves in the jaws. That the birds had developed along several widely divergent lines is shown by the fact that some which have been found in the Cretaceous rocks

were strong flyers, like the gulls, while others were wingless (Fig. 449) and spent their time exclusively in the water, where they had become as expert divers and fishers as the modern penguins of Antarctica.

FIG. 448. — A Cretaceous ammonite (Turrilites) with loose spiral form.

Crustal disturbances close the period. — Even before the close of the Cretaceous period various occurrences gave a hint of the revolutionary changes which finally brought the period to an end. In Mexico, British Columbia, and elsewhere volcanic eruptions took place on a considerable scale during the later part of Cretaceous time. At about the same time some portions of Colorado, Wyoming, and doubtless other regions were warped upward. That the resulting highlands suffered rapid erosion is shown by the coarser and more abundant sediments which were deposited around their borders.

These disturbances mark the beginning of a widespread

FIG. 449. — A toothed diving bird (Hesperornis) of the interior Cretaceous sea. (Painting by Gleeson. By the courtesy of McClure, Phillips and Company.)

epoch of crustal deformation, which resulted at the close of the period in the formation of many important mountain ranges, especially in the western hemisphere. Besides widespread warping and changes of level in western United States, the rocks were folded along a belt from Mexico to Alaska, and also apparently the entire length of South America. This marks the beginning of the present Rocky Mountains

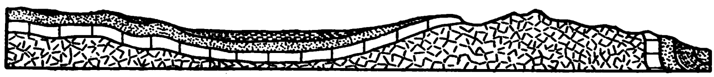

FIG. 450. — Gentle folds characteristic of the Rocky Mountains in Wyoming.

and the Andes, although the present height of those mountains is due chiefly to later movements. The folding in the Rockies at this time was by no means so intense as it was in the Appalachians at the close of the Permian. The folds are chiefly broad arches with troughs between (Fig. 450). Near the Canadian boundary the lateral compression was relieved not only by folding, but by a profound dislocation,

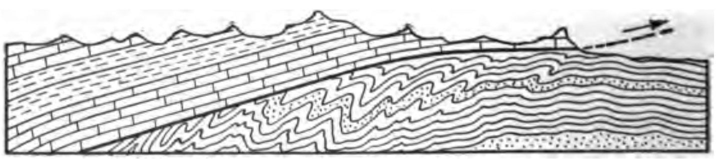

FIG. 451. — The great overthrust in the Rocky Mountains of Montana. The Proterozoic rocks on the left have been pushed up over the Mesozoic rocks on the right.

the older rocks having been pushed up over the Mesozoic strata along a great thrust plane. At one point the Algonkian rocks have been thrust out over the Cretaceous beds to a distance of at least seven miles (Fig. 451).

While the folding and warping were in progress, volcanoes came into existence in many parts of western America. Volcanic mountains comparable to the modern cones of Vesuvius and Fujiyama were built up in Colorado, Montana,

and other western states, as well as in South America. These were, however, only the first of a series of volcanoes which grew up during the Tertiary period (Fig. 452). The earlier ones became extinct so long ago that they have been worn down, but the latest of them we still see in such great peaks as Mt. Rainier and Mt. Shasta.

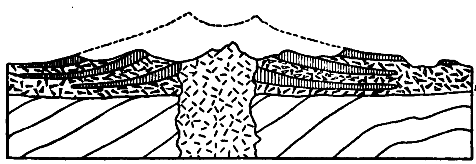

FIG. 452. — Section of a Tertiary volcanic cone the upper part of which has been removed by erosion. The lava flows are vertically shaded. They are interbedded with fragmental deposits.

Rapid changes in the animal life. — We naturally expect to find that the exclusion of the shallow seas which overlapped the continent in the Cretaceous period, the growth of mountain ranges where there had been lowlands before, and the accompanying changes of climate had a marked effect upon the living things. Thus at the close of the Cretaceous period, the ammonites, which had long been abundant in the seas, died out in a comparatively short time, leaving no descendants. Among the reptiles the change was quite as marked, although not as complete. Almost all the great reptiles which were so characteristic of the Mesozoic era became extinct, and only the smaller forms which we have to-day, such as the snakes, lizards, and turtles, lived on. The crocodiles seem to be the only remaining representatives of the large Mesozoic reptiles.

At the same time the mammals began a rise which in the next period became extraordinarily rapid. The appearance of the higher mammals in North America seems to have been sudden, as if they had immigrated from some other locality in which they had slowly developed from simpler forms. If this is true, the place of their origin is not yet known. Whether or not the rapid spread and growth of the mammals was responsible for the disappearance of the great reptiles is an open question, but the suggestion is at least plausible.

The Mesozoic Era in North America

Changes in the form of the continent. — At the close of the Paleozoic era the continental platform of North America had been left largely above the sea. Only on the Pacific coast did the ocean come farther inland than now. On the east side of this extensive continent stood the rugged mountains of the Appalachian system, perhaps not unlike the Andes of to-day. In the West lay broad, arid plains with occasional salt lakes, but it is improbable that high mountains stood there at that time.

As the era continued, the sea tended more and more to overspread the land. Late in the Jurassic period a long gulf came in across the depressed lowland which is now occupied by the great mountains of western Canada. A little later the Atlantic Ocean began to encroach upon the eastern and southern border of the continent, and along its shores were deposited the earliest sediments of the present coastal plain. Finally, in the Cretaceous period, the depression of the central western part of the continent allowed the sea to submerge a broad strip extending from the Arctic Ocean to the Gulf of Mexico, thus leaving North America divided into two smaller land masses.

The scene of earth movements, like that of sedimentation, was shifted to the West in the Mesozoic era. Not being resurrected by further warping, the Appalachian Mountains in the East had been gradually worn down to low hills with broad valleys between. They remained in this condition through the later part of the era. The crumpling of the Pacific coast strip had doubtless produced a series of great mountain ranges, among the descendants of which are the Sierra Nevada, Cascade, and Alaskan ranges of to-day. After a long period of comparative quiet during the Comanchean and Cretaceous periods the level strata of the western interior were arched and locally complexly folded, thus establishing the third great North American mountain system, —

the Rocky Mountains. By the retreat of the inland sea at about the same time, the continent was left more nearly in its present condition than ever before.

Climatic conditions. — In the Mesozoic, as in earlier eras, the climatic conditions left but scanty records from which we may now draw inferences. Extensive red beds give evidence of an arid climate over large areas in western United States, Europe, and China; but such conditions may have been due to the same local factors which produce deserts to-day. It is thought that the growth of abundant corals and other tropical animals in northern Europe in the Jurassic period indicates a much warmer general climate than the present. There are also differences in the faunas of northern, middle, and southern Europe and North America which may be due to climatic zones. That such zones have been in existence throughout geologic history can hardly be doubted, but, as already said, evidence of their presence in the earlier periods is scanty. It is quite probable, moreover, that the zones have been more distinct at certain times than at others.

Evolution of higher types of animals and plants. — When the Mesozoic era began, the old Paleozoic ferns and seed ferns were sinking into a subordinate place, as the conifers, cycads, and other naked-seed plants came to the front. Before the end of the era, however, even these were superseded in large measure by the modern flowering trees, shrubs, and grasses. By this change the landscapes doubtless came to look much more like those which we now see.

Early in the Mesozoic era the reptiles were in the youth of their race, rapidly developing and rising to their zenith before the Comanchean period. Having mastered the life of the dry lands, the shallow seas, the air, and even the open oceans, they kept their dominant place until the end of the era. Their later years were marked by inability to compete with the rising mammals, and it is perhaps for this reason that they were soon relegated to the background. Other groups of animals underwent corresponding, if per-

haps less striking, changes; and when the next era opened, all the large groups, except the birds and the mammals, had nearly reached their modern condition.

Questions

1. In the drier parts of South Dakota the Cretaceous shales contain many little lenses of limestone. These now stand out as conical hills, known as "tepee buttes" from their resemblance to an Indian tent. If the climate of this region were moist and the surface densely forested these buttes would probably not be formed. Why?

2. The Dakota sandstone is exposed along the flanks of the Rocky Mountains in sharp ridges, locally known as "hogbacks." What does this tell about the character of the formation?

3. Some of the Cretaceous chalk is interbedded with layers of sandstone. What does this indicate about the depth of water in which the chalk was formed?

4. In some of the Cretaceous beds sticks of wood with charred ends have been found. What inference is suggested?

5. Chalk consists largely of the shells of protozoans. What are the habits of these animals? Under what conditions do they succeed in forming a deposit of chalk?

6. About the Black Hills of South Dakota the Laramie beds appear to contain no material derived from the Paleozoic group, while the Tertiary beds which lie upon the Laramie are largely composed of such débris. How may this be explained?

7. Bees, butterflies, and many other insects of like habits have not been found in rocks older than Cretaceous. How may this fact be related to evolution among the plants?

CHAPTER XXIV

THE TERTIARY PERIOD

Results of the warping and folding. — The crustal disturbances which brought the Mesozoic era to a close wrought great changes in the land forms on the continent of North America. In the Appalachian region a broad swelling or upwarp of the Cretaceous peneplain [1] had raised its surface some two or three thousand feet, and the streams, thus rejuvenated, were already engaged in etching out the softer strata, leaving the harder ones protruding as mountain ridges.

The great central portion of the country had been raised very little, but in the Cordilleran region of the West, the comparatively low-lying Mesozoic surface had been converted into mountains of considerable height with intervening basins and valleys. There, as in the Appalachians, the hills and mountains were being worn down and the resultant sediments were filling up the lowlands.

Divisions of the period. — The Tertiary period, while perhaps no longer than many that preceded it, is of course much better known, because it is nearer the present. It is usually divided into several epochs [2]: —

(3) Pliocene (more recent).
(2) Miocene (less recent).
(1) Eocene (dawn of the recent).

Additions to the Atlantic and Gulf coastal plain. — From New England south to Florida, and almost encircling the Gulf of Mexico, the Tertiary sediments are found lying upon the Comanchean and Cretaceous deposits which had formed

[1] See page 414.

[2] Of these, the Eocene is probably much longer than either of the others, and is often divided into Eocene (proper) and Oligocene.

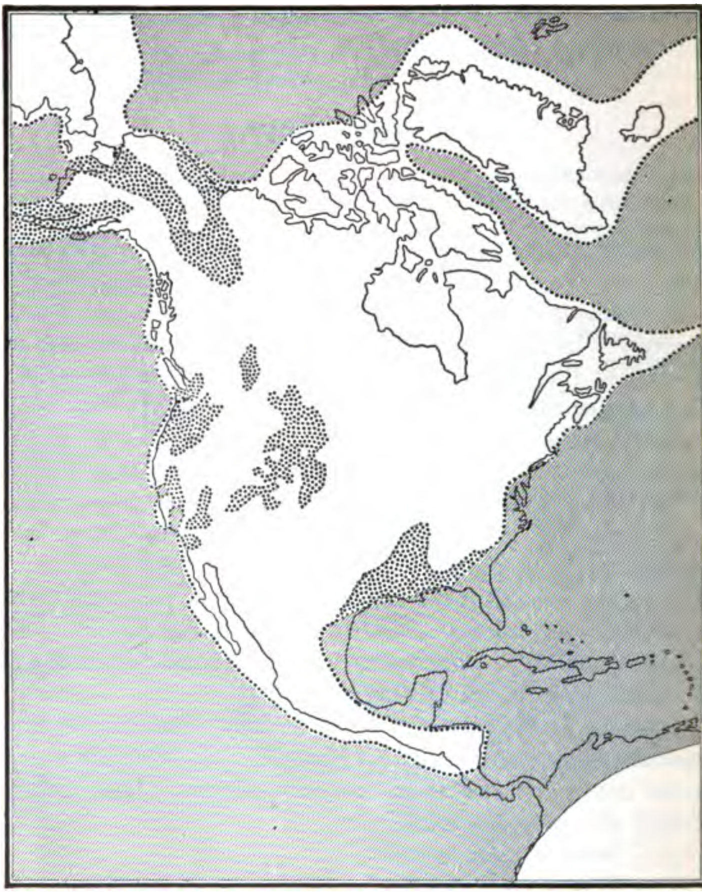

FIG. 453. — Supposed outline of North America early in the Tertiary period. The dotted pattern represents deposits made on land. (Modified after Willis.)

the beginning of the coastal plain. Some of these Tertiary rocks are sand, peat, clay, and marl, and some are soft limestone or chalk. They are interrupted by a number of slight unconformities. In these deposits and unconformities we find recorded the fact that the eastern and southern margin

of the continent was sometimes submerged, and was thus the site of deposition; and that at other times it was out of water, and was liable to erosion. The changes of level, whether of the land or of the sea, were not great in any instance. One result of the slight warping to which eastern United States was subjected during the Tertiary period was the formation of an island within the present confines of Florida, and later the addition of this island to the mainland in the form of a peninsula. No deposits older than the Tertiary limestones are exposed in that state.

At several places in Texas, Louisiana, and California wells drilled down into the Tertiary sediments have yielded petroleum. This oil, and the natural gas which usually accompanies it, is probably produced by the slow decomposition of animal and vegetable matter which was mixed with the sediments at the time they were deposited. Certain sandy beds become saturated with the gas and liquid and when one of these is pierced by the drill a flowing well may result. In some cases the gas pressure is so great that the oil is blown out in a jet. These "gushers" often wreck the buildings and derricks over the wells, and much oil is wasted before the fountain can be controlled.

Only a part of the oil produced in the United States comes from Tertiary beds. That of Ohio and Indiana is in the Paleozoic rocks, and the Kansas oil is only a little younger. Doubtless the conditions for the formation of gas and oil have been present somewhere in all the geologic periods.

Local sedimentation on the Pacific coast. — In the Tertiary period, the Pacific coast was apparently somewhat abrupt and rugged, although perhaps less so than it is to-day. Erosion was the chief activity along the western slope. Here and there, however, deposits of Tertiary age have been found, those in the coast ranges of California being largely of marine origin, while farther north, near Puget Sound and in Alaska, early Tertiary beds containing coal seams are known. The latter were evidently laid down in swampy lowlands near the coast, but not submerged by the sea.

Alluvial deposits in the Great Plains. — Throughout most of the Tertiary period the Great Plains were much nearer

sea level than now, and less intrenched by valleys. Many streams which issued from the newly made mountains on the west were spreading their loads of gravel, sand, and mud far and wide over the low-lying surface. Here and there lakes and marshes doubtless existed temporarily, and the location of these shifted from time to time, so that the deposits which now represent the Tertiary in the Great Plains are partly such as are laid down in lakes, and partly those which rivers and even winds make. In the Tertiary epochs the climate of the Great Plains region was on the average moister than it is to-day. Coaly layers in the Tertiary strata indicate the existence of swamps, where now only dry prairies are to be found. The Tertiary deposits, which have since been elevated and subjected to a drier climate, are now being rapidly dissected by the growth of ramifying valleys and tributary gullies. In parts of Dakota and Montana the result is an extremely rugged complex of ridges, mesas, and buttes, over which travel is very difficult, and which are therefore known as "Bad Lands" (Fig. 454).

Changes affecting the western mountains. — The young Rocky Mountains and others farther west were being rapidly worn down by the activities of wind, rain, and streams. Some of the material thus furnished found lodgment in the interior basins between the mountain ranges, and there accumulated to great thickness. As in the plains, these deposits were made partly in lakes, but are to be ascribed in large measure to the work of streams which built alluvial fans in front of the valleys they had cut in the mountain slopes. Coalescing with each other, these fans came to form alluvial plains.

In addition to the sand, gravel, and silt, beds of volcanic ash and sometimes of coarser tuff are found included in these Tertiary strata. They record the eruptions which took place at intervals from the volcanoes in Colorado, Montana, and many other western states while the Tertiary sediments were being laid down. The old volcanic cones have been

FIG. 454. — Bad Land topography in South Dakota. (Darton, *U.S. Geol. Surv.*)

slowly worn down, but their cores and remnants of the old lava flows may still be recognized.

Most of the ore deposits which have given the western states their renown as mining districts are connected with the volcanic intrusives of Tertiary times. The gold, the discovery of which caused the rush of immigrants to California in 1849 and succeeding years, was found partly in gravels in the valleys of Tertiary rivers. The famous gold mines of Cripple Creek, Colorado, and the copper mines of Butte, Montana, and parts of Utah, all get their ores from veins adjacent to bodies of porphyry and other igneous rocks which were forced into the older formations in the Tertiary period. In this respect there is a contrast between the western and eastern mountains of the United States.

The climate of the mountain region could not have been as arid as it is to-day, for the luxuriant vegetation which flourished there in the Tertiary period shows that the rainfall was plentiful. In some of the driest parts of Utah and

Wyoming the Tertiary strata have preserved abundant leaves of palms, figs, and magnolias. The present dryness is doubtless to be ascribed in part to the later uplifting of the present mountain ranges which shut off the moist winds from the Pacific Ocean.

Mountain growth. — In the West, the Eocene epoch was occupied largely in the wearing down of the highlands which had been produced at the close of the Cretaceous period, and in the filling of the lowlands. Warping and volcanic activity, although they had not ceased, were of minor importance. It was an epoch of quiescence.

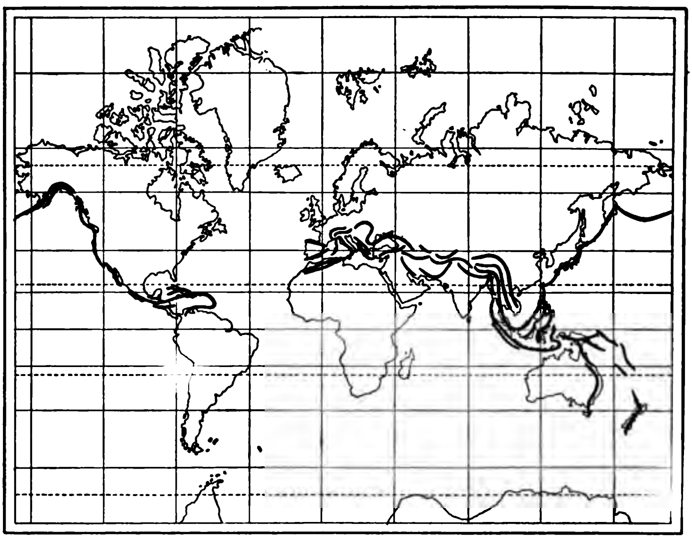

FIG. 455. — Trend lines of folds made during the middle Tertiary epoch of mountain-building.

Near the middle of the Tertiary (Miocene epoch), however, the disturbances were renewed on quite as grand a scale as before, but in part along different lines. One of the greatest results of this deformation is now seen in the series of high mountain chains which partially encircles the globe north of the equator (Fig. 455). In our own hemisphere it

is represented in the mountains of Cuba, Porto Ríco, and southern Mexico (Antillean system). (See Fig. 44.) These ranges are less conspicuous than some of the mountains on the land, only because they are largely submerged. The highest peaks of Cuba rise more than twenty-five thousand feet above the floor of the adjacent Caribbean Sea. In the old world the eastward trending mountains, from the Pyre-

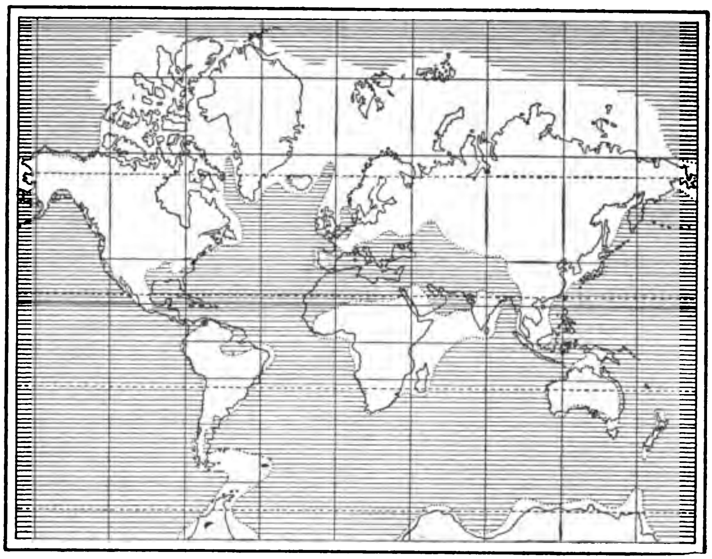

Fig. 456.—Geography of the world as it is thought to have been at a time early in the Tertiary period. Note the continuous land in the northern hemisphere, with isolated continents in the south.

nees in Spain, through the Alps, Caucasus, and many other ranges, to the Himalayas and far beyond, belong to this great belt of Tertiary mountains. Hitherto most of these regions had been beneath the sea; on the site of even the great Himalayas there was, up to the early part of the Tertiary period, a broad sea, not unlike the Mediterranean (Fig. 456). In this sea limestone was being quietly formed. But in the Tertiary disturbance these and all older rocks

of this locality were folded, compressed, and raised into lofty ridges which are now being carved by erosion into rugged mountains.

A little later, the Sierras, Rockies, and other western ranges began a renewed epoch of growth; this time not chiefly through folding, as at the close of the Cretaceous period, but by mere warping and faulting. The rise of the Sierra range and its northward continuations consisted of an arching of the surface; but locally, as along the east base of the Sierra, the arch cracked (Fig. 457), or, in other words, was faulted, and that side is now much steeper than the slope toward the Pacific. There is good evidence that the slow uplifting of the Sierra is still going on, for as recently as 1872 a slip of nearly twenty-five feet occurred along this fault plane.

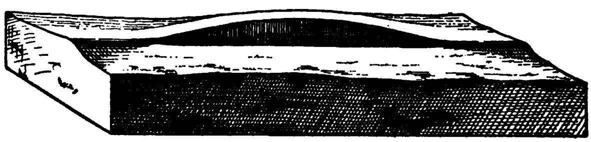

FIG. 457. — Stereogram of a low fold broken on one side.

Tertiary volcanoes. — In this western region volcanic eruptions continued, but with somewhat decreasing activity. They have only very recently ceased, and it is in fact by no means certain that the present is anything more than a temporary period of quiet in that respect. Near the middle of the Tertiary period, eruptions of lava from fissures as well as from volcanic craters took place over a vast area in the northwestern part of the United States, particularly in Idaho, Washington, and Oregon. Flow after flow of liquid lava welled up through cracks in the earth and poured out over the surface, leveled up its inequalities, and finally produced a plateau more than a thousand feet in height and equal in extent to several good-sized states (Figs. 25, 458). Similar eruptions have occurred occasionally in earlier periods, but nothing quite like them has been observed in historic times.

The renewal of the uplifts late in the Tertiary and continuing into the next period brought on the conditions which we now think of as characteristic of the region. It is to these later movements that the present elevation of our

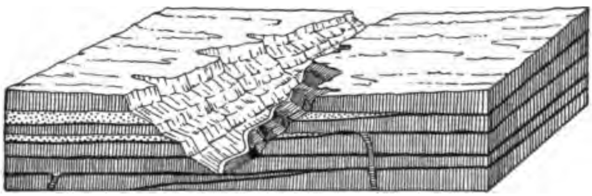

FIG. 458. — Stereogram of a part of the Columbia River lava plateau, showing flows with interbedded layers of sand and gravel.

high ranges is due; and, as has been said, in some of them the growth is still in progress. During the uplifts, the streams sank their valleys deeper and deeper into the lands, so that the West is now characterized, not only by mountain ranges, but by high plateaus deeply cut by cañons,

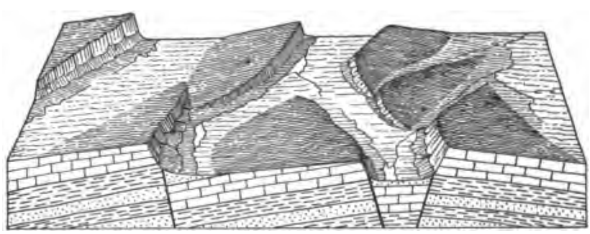

FIG. 459. — Young fault block mountains in southern Oregon. (Modified after Davis.)
Why are the depressed spaces between the blocks flat?

such as those of the Colorado and the Snake rivers. The growth of the mountains also deprived the winds from the Pacific of a large part of their moisture, and thus condemned the interior basins and the Great Plains to a much drier climate than they had before.

Life of the Tertiary Period

Modern aspect of the lower forms of life. — Before the Tertiary period, all the important types of plants had made their appearance, and the flowering group had taken the place it now holds in the lead. The lower groups of animals had likewise become much like those we have to-day. The trilobites, brachiopods, ammonites, and other ancient divisions had given way to modern groups of crustaceans, bivalves, cuttlefish, and others. The fishes, amphibians, and reptiles had passed their prime and were represented in the Tertiary period only by species resembling those now living.

Only the birds and mammals, then, claim our interest, because they alone are still progressing. Of these, the mammals are much the more important, and have left us the better-preserved fossils. They are now the highest and most powerful of the animal groups.

Generalized mammals of the Eocene epoch. — Among the beds of sand and clay which were laid down in the broad Eocene valleys of our western mountain region and certain other parts of the world, abundant skeletons of mammals have been found. They show that many kinds were even then in existence, that they differed considerably in their habits of life, and that they were already the leading animals of their time. At the present day we have no difficulty in distinguishing the several large groups of mammals from each other. Thus we have the flesh eaters (Carnivores), such as the tiger, bear, and wolf; the hoofed mammals (Ungulates), such as the horse, buffalo, and deer; the gnawers (Rodents), such as the squirrel and rat; the whales and dolphins (Cetaceans), which are swimmers exclusively; and still others. It is difficult, however, to place the early Tertiary mammals in these familiar divisions. Instead, we find varieties which seem to have combined the characteristics of several later groups. For example, it is possible to trace

the horse, deer, and rhinoceros families, with their specialized hoofs and grinding teeth, back to a peculiar five-toed animal which had a full set of rather simple teeth, and was no larger than a dog (Fig. 460). This Eocene form seems to be an ancestral or *generalized type* from which the later hoofed animals diverged and ascended. Furthermore, it resembles in many respects the equally generalized ancestors of the dogs, bears, and cats, although cats and horses, for example, to-day seem to have little in common.

FIG. 460. — A generalized hoofed mammal (Phenacodus) which lived in North America near the beginning of the Tertiary period. (Painted by C. R. Knight, under the direction of Professor H. F. Osborn. Copyright by the *Amer. Mus. of Nat. Hist.*)

Rapid evolution of the mammals. — The progress of these generalized mammals of the early Eocene was astonishingly rapid. In each later series of deposits the bones of new and more modern varieties are found. Thus, before the middle of the Tertiary period (Miocene), the main divisions of the mammals became entirely distinct and we may easily recognize cats, horses, monkeys, whales, bats, elephants, and

many other kinds. True, they were not the same species which exist to-day; some of the horses, for example, had three toes instead of one, as they now have; but the types were unmistakable. Before the close of the Tertiary, the older and more primitive mammals had been exterminated from the northern continents, and the whole animal kingdom had taken on very largely its present aspect.

FIG. 461. — Ancestral Eocene horses (Eohippus) with three and four toes on the feet. (Painted by C. R. Knight, under the direction of Professor H. F. Osborn. Copyright by *Amer. Mus. of Nat. Hist.*)

The mammals adopt many modes of life. — As mentioned in Chapters on the Mesozoic era, the reptiles when in their prime had occupied the forests, the plains, the marshes, the seas, and all other situations in which animals could well exist. In the Tertiary period we find the mammals stepping into the places relinquished by the reptiles, perhaps after having actually displaced them by sheer victory in competition. Thus

we have mammals of the forest (for example, squirrels), of the plains (antelopes), of the marshes (beavers), of the air (bats), of the ocean (whales), and many more.

Interestingly enough, as the mammals adopted these modes of life, they often took on in a degree the form and appearance of their reptilian predecessors. To appreciate this one has only to compare the bat with the pterosaur (Fig. 435), the porpoise with the fish reptiles (Fig. 421), and the rhinoceros with the heavy dinosaurs (Fig. 433).

Migrations of the Tertiary mammals. — There are to-day some very peculiar things about the distribution of certain animals which are explained only when we study the fossils from the Tertiary formations. The camels are now found in Asia and Africa, and also in the Andes Mountains of South America. In Tertiary times, as the fossils show us, they roamed widely over western North America as well, and it seems probable that they migrated thence to Eurasia by way of Alaska at a time when that peninsula was less submerged than now and enjoyed a warmer climate. Later they died out in North America. This is but an instance of many migrations by which the mammals of Eurasia and America mingled during the Tertiary period.

Some islands were so isolated by water that they could not be reached by the mammals which originated in the larger continents. Australia is a case in point. There we find almost none of our familiar higher mammals, but instead a host of peculiar marsupials, among which are kangaroos, wombats, and opossums. It is known that these marsupials are most closely related to animals that lived in Europe in the Mesozoic era, but died out there early in the Tertiary period. The inference is that Australia has been isolated from the other lands since perhaps the Cretaceous period, and that during the Tertiary period her peculiar mammals evolved along their own lines without that interference which comes from sharp competition with the more progressive higher animals.

South America and Africa were similarly isolated at certain times, but later in the Tertiary period they were linked with the northern lands and thence received the tide of immigrants belonging to the more advanced mammals.

By studying the present distribution of animals and working out the paths of their earlier migrations, we can learn much about the changes which have taken place in geography during the later periods. The map (Fig. 456) shows roughly how the continents and seas are thought to have been arranged in early Tertiary times, as compared with the present.

Questions

1. The Eocene coal in the vicinity of Seattle is bituminous and locally even anthracitic; that in Mississippi is soft lignite. Without further information, what predictions would you venture as to the geological conditions in the two regions?

2. It has been suggested that the climatic changes known to have taken place in the Tertiary period may have been caused partly by changes in the ocean currents. What would happen to-day if Florida joined Cuba and the Bahama Islands, while at the same time Central America were submerged deeply?

3. Can you suggest why the known deposits of Eocene age are largely those which were made on the surface of the land?

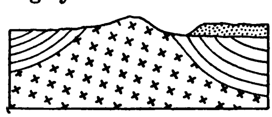

Fig. 462. — Section of mountain range. The folded beds are Paleozoic and Mesozoic. The horizontal bed is Miocene. (Vertical scale, 1 in. = 10,000 ft.)

4. The accompanying diagram (Fig. 462) represents a mountain range in the West. Show how the depth of erosion early in the Tertiary may be estimated from such a section.

5. The Eocene strata of Wyoming include beds of limestone with fossil fishes. From your knowledge of Tertiary geography what do you suspect was the origin of these beds?

6. What events or conditions are recorded in the following sections (Figs. 463, 464, and 465) selected from the Tertiary strata in different parts of the United States?

Fig. 463. — Limestone (Florida).

7. The pyramids of Egypt were built of Eocene limestone. What change must have taken place in this deposit of shells since it was formed?

8. In Thibet, marine limestone of Eocene age has been found at altitudes of 20,000 feet. How much of the history of Thibet may be inferred from this fact?

9. On the western slope of the Sierra Nevada range there are flat-topped ridges capped with sheets of lava (Fig. 466). Beneath the lava gold-bearing gravels have been found. Can you suggest how the present conditions were brought about? What would be the best method of mining the gold in these deposits?

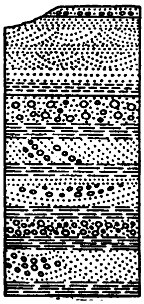

Fig. 464. — Alternate shale, sandstone, and conglomerate (Colorado).

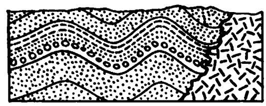

Fig. 465. — Conglomerate, sandstone, and shale, in contact with a mass of granite (Oregon).

Fig. 466. — Diagram of a lava-capped ridge in California.

CHAPTER XXV

THE QUATERNARY PERIOD

The great ice sheets. — During the later part of the Tertiary period the climate of the northern regions was becoming somewhat colder, so that palms no longer flourished in Greenland, nor corals off the coast of Scotland, as they had in the early Tertiary. In the Quaternary period, from causes not yet understood, the temperature of the northern regions had been lowered to such a degree that the snows of winter were not melted off in summer. Thus glaciers came into existence, not only in high mountains and polar regions where we have them to-day, but over large regions which are now free from them. Through the long accumulation of snows, thick ice sheets, or continental glaciers, grew up in North America and in Scandinavia and spread outward in all directions until they covered Canada and much of Europe.

In North America the ice sheets extended into the United States as far south as southern Illinois and New Jersey. Singularly enough, they did not cover much of Alaska, in spite of the fact that it is farther north than some of the countries which were glaciated (Fig. 467).

The fact that ice sheets did not cover Alaska and Siberia, two of the coldest parts of the world, shows that low temperature was not the only condition needed to bring on glaciation. Plenty of snow is likewise essential, and so in rather dry regions or where there are short, hot summers, even where there is great cold, we find no glaciers.

Successive advances and retreats of the ice. — The *Glacial epoch* was marked by the growth and eventual melting off of not merely one ice sheet but of several, one after the other. This is true of both Europe and North America. In the

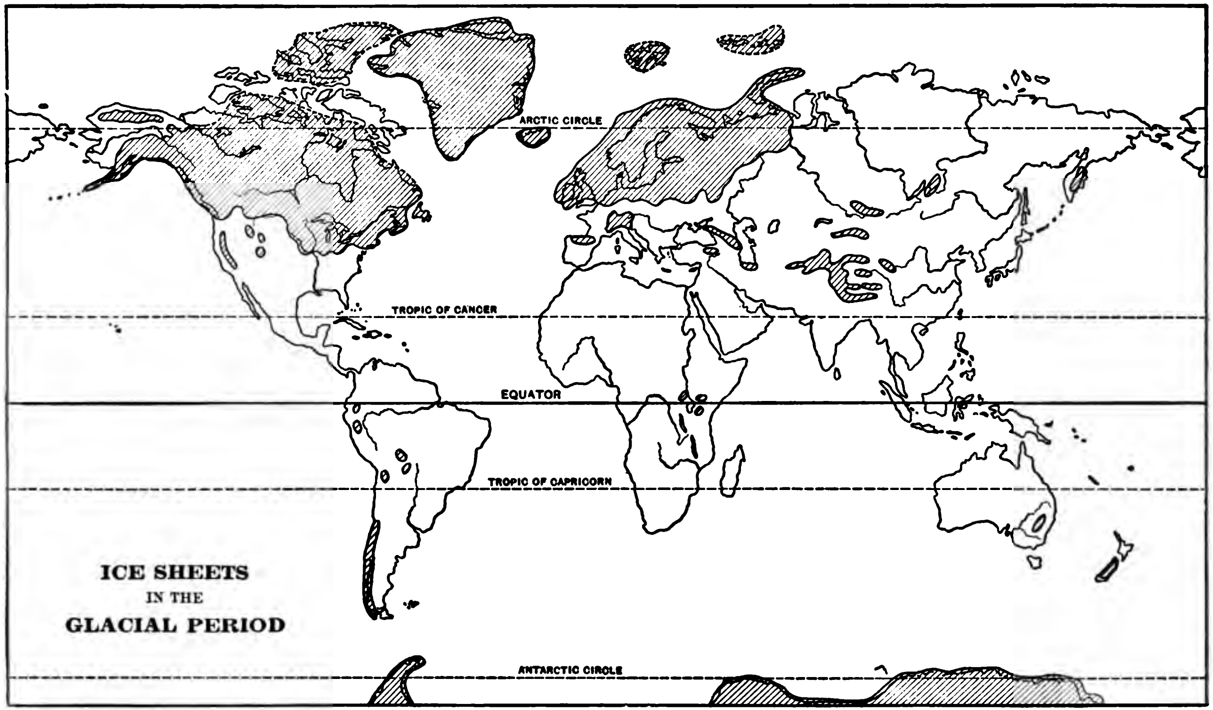

FIG. 467. — Distribution of ice sheets and smaller snow fields (shaded) during the Glacial epoch.

Mississippi Basin evidence of several advances and retreats has been discovered. The greatest extension was reached by the second ice sheet, which spread southward almost to the mouth of the Ohio River; but later ones fell only a little short of that. Between the several advances, the ice sheets seem to have entirely disappeared or to have been reduced to much smaller size. That these disappearances were caused by periods of warmer climate is shown by the finding of leaves of southern plants in clay beds between two layers of glacial till as far north as Toronto in Canada. Trees now characteristic of the Ohio Valley then lived abundantly north of Lake Erie.

In view of the fact that ice sheets grind down the surface over which they slowly creep, we need not wonder that the later ice sheets removed much of the deposits left during preceding glaciations. Even where the earlier sheets of drift were not destroyed, they are now largely buried by deposits of the later ice sheets. We therefore know the older drift best around the edges of the newer. Its greater age is indicated clearly by the fact that it has been deeply trenched by branching systems of valleys which have been growing and extending themselves through all the time since the early deposits of drift were laid down. The last drift sheet was made so recently that the streams have barely begun this work of trenching, and its usually rough surface is still dotted with undrained lakes and marshes.

Estimates of the length of the Quaternary period. — Many attempts have been made to estimate the number of years represented by the glacial advances and retreats. At present the cliff at Niagara Falls is being cut back several feet per year. It has been calculated that at some such rate it would take from 7,000 to 50,000 years to cut the entire gorge below the falls. Since the falls could not have begun until after the last ice sheet had retreated to Lake Ontario, a somewhat longer time would be required to take us back to the beginning of the retreat of the latest glaciers. By compar-

ing the effects of weathering and erosion on the older and younger sheets of drift it is possible to gain a rough idea as to their relative ages. Estimates thus made of the length of time since glaciation began range from 500,000 to 1,500,000 years. It is impossible to make a much closer calculation than this because there are so many factors which vary from time to time and in a way which cannot be predicted. But the fact is clear that the period was many times as long as the known part of human history.

How the ice sheets changed the land surface. — The work of glaciers has already been discussed in Chapter VI. There it was shown that the effects wrought by glaciers are very different in different places. Thus the last Canadian ice sheets produced varied changes according as the country they invaded was flat, hilly, or mountainous.

In the mountains of New York the ice scoured off the slopes of the hills, and removed the crags and talus slopes, but did not greatly change the general forms (Fig. 468). Preëxisting valleys were scoured out and deepened where they ran parallel to the ice movement, and were partially filled with drift where their courses lay across the line of glacial movement. The so-called finger lakes of western New York are in valleys thus deepened and locally blockaded.

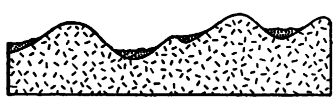

FIG. 468. — Low mountains which have been scoured by an ice sheet, leaving the summits smooth and rounded and the valleys partly filled with drift.

Where the hills were lower and the ice thicker in proportion, the effects of erosion by the ice sheet were more pronounced. Not only was a vast amount of soil and rock ground from the hills, but many of the preglacial valleys were completely buried (Fig. 469). In such regions the present hills and hollows are simply the irregularities of the drift itself, as it was deposited. The older topography has thus been obliterated over large areas of Illinois, Minnesota, and other northern states.

Disturbance of river courses. — Before the ice covered the northern region the many rivers had become in large meas-

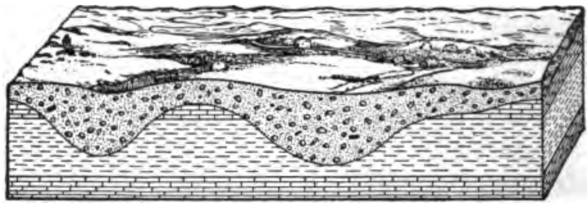

FIG. 469. — Preglacial hills and valleys obliterated by the deposition of glacial till. (After Tarr.)

ure adjusted to the hard and soft rocks in which they were excavating their valleys. As the ice overspread their basins many such valleys, with their rivers, were wholly destroyed, and the new streams which arose after the ice melted pursue courses quite unrelated to those of their predecessors. The Rock River in Illinois and Wisconsin exemplifies this (Fig. 470).

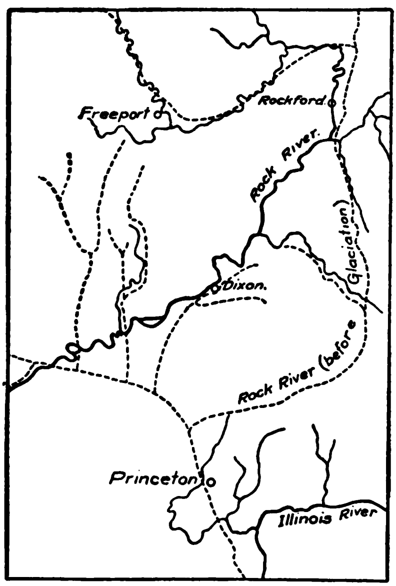

FIG. 470. — A portion of northwestern Illinois, showing the course of the Rock River before and after glaciation. (After Leverett.)

Other streams, especially those located near the margin of the ice sheet, were merely crowded to one side and forced to make new valleys. Thus the Missouri River appears to have been displaced by one of the earlier ice sheets. It cut a new channel along the front of the glacier

(*B*, Fig. 471), and even after the ice melted back again the river held its new course.

Marginal lakes of the retreat stage. — Like all ice sheets, those of the Glacial epoch pushed out lobes or tongues along the valleys near their margins. The ice sheet thus came to have scalloped edges. During the last retreat the great glacial lobes which had occupied such depressions ponded the waters between the moraines they had left and the front of the ice, thus producing a series of lakes (Fig. 473). The overflow water from these lakes ran southward, largely into tributaries of the Mississippi River, — Lake Superior draining out past Duluth and Lake Michigan past Chicago. As the ice retreated slowly northward the lakes grew in size and some joined those next to them to form larger lakes; while others, having lost the ice wall on one side, disappeared entirely. Our present Great Lakes began as marginal waters of this kind, and it was only after the ice had retreated into Canada that they were all connected and found the St. Lawrence Valley the lowest point of outflow.

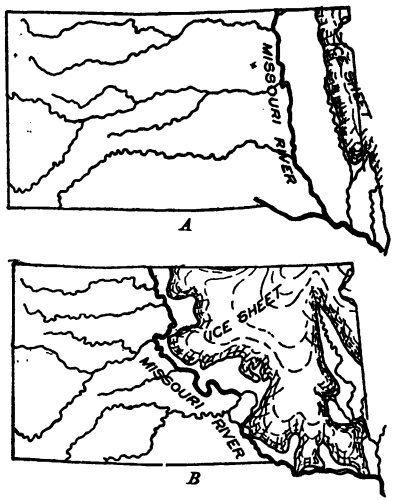

Fig. 471. — *A* and *B*. Diagrammatic maps of South Dakota, showing how the Missouri River was displaced by the invasion of an ice sheet. (Modified after Todd.)

As the ice retreated from Minnesota, the Dakotas, and Manitoba, it left a shallow basin in which another great lake came into existence. Lake Agassiz, as it is called, was once five times as large as Lake Superior, but when the ice sheet which blocked its northern edge finally melted away, the

waters of the lake were drained off, leaving only much smaller lakes, as Winnipeg, in the deepest parts of its basin. Its existence is now known from the many terraces and sandy beaches made by its waves, and by the broad, flat bottom built of fine silts which were deposited in the lake. This alluvial plain is now one of the richest wheat-growing districts in the world.

FIG. 472. — A modern glacier on the coast of Alaska, showing a marginal lake inclosed by a terminal moraine which is in turn fringed by an outwash plain. (Modified after Maddren, *U.S. Geol. Surv.*) Is the glacier retreating or advancing?

Features of the latest drift sheet. — We have already said that the older sheets of drift have been trenched by many valleys, so that the original moraines and other purely glacial features are no longer easily recognized. The last ice sheet (called the *Wisconsin*) disappeared so recently that, in general, erosive agencies have not had time to mar the surface of the deposits which it left.

Where the edge of the ice sheet lingered we now find terminal moraines. There the drift is usually thicker than elsewhere, and rough hills alternating with undrained hollows are characteristic. Many of the hills are composed of rudely stratified gravel heaped up in conical form. These kames are often excavated for road material and railroad ballast. On account of the roughness and bowldery soil of the terminal moraines, they are not commonly cultivated, but are left as woodland and pastures.

Lakes are especially abundant in the terminal moraines. In Minnesota and Wisconsin thousands of them mark the positions of these belts.

Stretching southward from the moraines, gently sloping plains mark the outwash deposits which were built by the overloaded glacial streams. Owing to the porous, well-

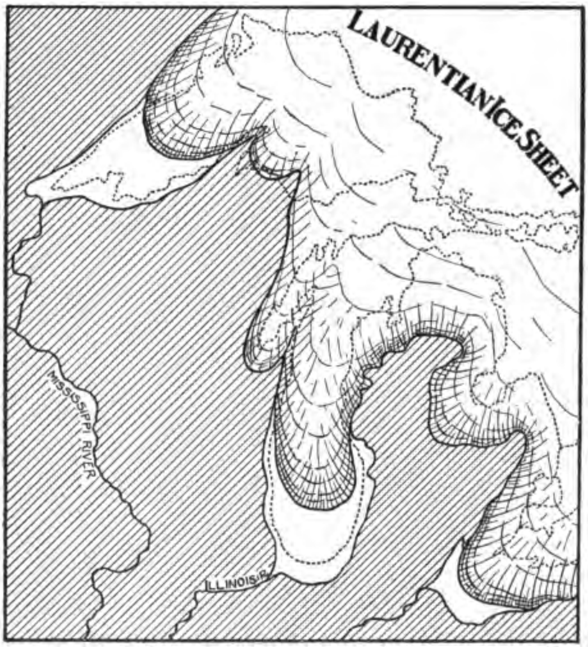

FIG. 473. — Lobate edge of the American ice sheet with marginal lakes left during its retreat. (Modified after Taylor and Leverett, *U.S. Geol. Surv.*)

drained soil, some of these plains make excellent farming land, although others are too sandy. Down every valley leading away from the moraines, gravel and silt were strewn, forming a flood plain. When the glaciers disappeared and the streams became relatively free from detritus they were able to cut down into these valley trains and have left portions of them as terraces.

Back of the terminal moraines, over wide areas, the ground moraine prevails, — an undulating plain with gentle slopes. Lakes and marshes strung on crooked, aimless streams are of common occurrence (Fig. 474). Where the drift is thin, rock hills may protrude, their rounded forms and polished, grooved surfaces showing plainly the wear of the ice sheet upon them. Elsewhere the entire surface is molded from the glacial bowlder clay. In such districts there may be drumlins, — smooth, elliptical hills of till all trending parallel to the direction in which the ice was moving.

The successive advances and retreats of the ice made the distribution of these several features less simple than might be

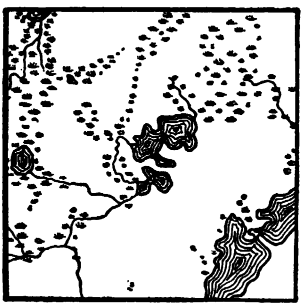

FIG. 474. — Aimless drainage of a glaciated region, eastern Wisconsin.

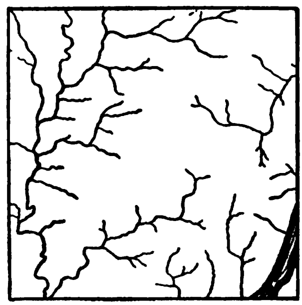

FIG. 475. — Tree-shaped drainage systems in an unglaciated region, northeastern Iowa.

expected. Readvancing ice plowed over and defaced drumlins and moraines which had been left at an earlier stage. Outwash deposits of stratified drift made in front of such an advancing glacier were often worked over and buried under a sheet of till. Later, outwash sands and gravels were spread over moraines as the ice retreated. The escaping water ponded behind terminal moraines cut channels in them here and there.

Some of the effects of glaciation on human affairs. — Mention has already been made of the excellent soils usually found upon glacial lake floors and outwash plains. The finely pulverized rock material left generally over the glaciated

regions is on the average a better soil than the residual sandy clays which are produced by the ordinary weathering of many rocks. In some places, notably in parts of New England and eastern Canada, however, the till contains so many bowlders that cultivation of the soil is very laborious. Among the best harbors in the United States are the glacial fiords and bays of the New England coast. These facilities early helped to lead the people of the region to engage in fishing and to become the best seamen and shipbuilders of the country.

The general derangement of rivers by the ice sheets hindered inland navigation in a measure, but at the same time it conferred large benefits in the form of available water power from the many falls and rapids. The abundance of these falls near the centers of trade in northeastern United States has assisted in making that region a great manufacturing district. As the progress of invention makes it possible to transmit electric power over longer and longer distances, these falls will be used more extensively; and as the fuel resources of the country are gradually depleted, more and more dependence will be placed on electricity from water power. The glaciated regions are thus likely to retain their interest and importance in the manufacturing industry.

The Glacial Epoch outside of the Ice Sheets

In the rest of the United States and in other continents the events of the Quaternary period were much like those of the preceding Tertiary. By the erosion of running water, plateaus were being cut into hills and mountains, winds were carving out the softer rocks in the deserts, and waves were eating back the rocky coasts. Along low-lying plains and river bottoms, gravel, sand, and mud were strewn; while the waves and winds built barriers and sand dunes along the edges of the shallow seas.

There is a decided contrast between the conditions and appearance of the recently glaciated and the unglaciated parts of the land (Figs. 474 and 475). Over much of the region where

the last ice sheet left its deposits there are lakes, marshes aimless rivers, waterfalls, and scattered bowlders. Elsewhere lakes and marshes are confined largely to the river bottoms and seashores; waterfalls are few; the rivers are grouped in branching, treelike systems; bowlders from distant regions are not to be found; and the hill soils are chiefly residual.

Valley glaciers in the mountains. — In the mountains to-day there are small valley glaciers wherever there is sufficient cold and snowfall. In the Glacial epoch these were larger than now and vastly more numerous. Only the lower ranges in western United States were free from them. It is easy to identify the places where these alpine glaciers have been at work, long after they have passed away, for they not only scoured and striated the valley floors, but made the original valleys U-shaped, sharpened the mountain peaks into crags and pinnacles, and built loop-shaped morainic ridges farther down the valleys. Along the abandoned valleys many lakes now testify to the work of the ice. The wild scenery of the high, snowy ranges to-day is due largely to the sculpturing by Quaternary glaciers.

Great Quaternary lakes of Utah and Nevada. — The basin which lies between the Rocky Mountains and the Sierra Nevada is now arid, and most of the rivers flowing into it dwindle away in the desert soils, or feed salt lakes from which no streams flow out. During the Glacial epoch, all of these lakes were much larger than now. Great Salt Lake in Utah is only a remnant of a lake, called *Bonneville* (Fig. 476), which was two thirds as large as Lake Superior and one thousand feet deep. The former existence of this great lake is shown plainly by the series of cliffs and terraces which parallel the slopes of the adjacent mountains (Fig. 477). These terraces were made by the waves on the lake. At that time, Lake Bonneville overflowed northward into the Snake River. In lakes with outlets the water is continually being changed and so is not allowed to become salty. Bonneville was therefore a fresh lake. In western Nevada a series

of valleys was filled at that time by a most irregular lake which has been named *Lahontan*. In the drier recent epoch

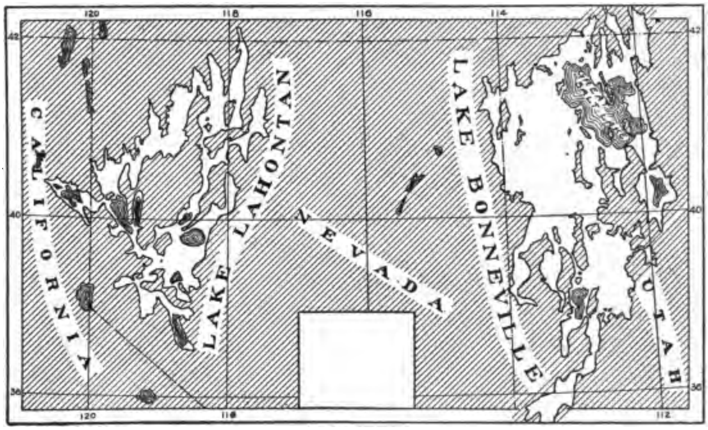

FIG. 476. — Quaternary lakes of western United States.

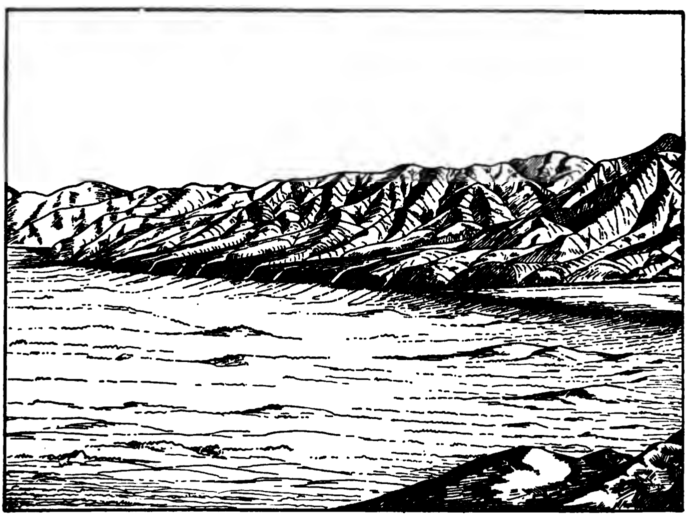

FIG. 477. — An abandoned shore line of Lake Bonneville. (After Holmes, *U.S. Geol. Surv.*)

its water, like that of Lake Bonneville, has largely evaporated, leaving several small, salty lakes and dry, flat-bottomed depressions covered with sand and crusts of lime. These deserts were fatal to some of the early emigrants to California who came overland from the East.

Decline in volcanic activity. — While volcanoes were less numerous in the West during this period than in the Tertiary they were still fairly common, as is attested by numbers of small cinder cones among the western mountains and high plateaus. In the bed of old Lake Bonneville several little craters were formed after the lake shrank to nearly its present size. In northern California there is another little cone surrounded by a recent lava flow and a layer of ashes in which the stumps of trees killed by the last eruption are still standing. The great cones of Mts. Shasta, Rainier, and others along the Pacific slope, which were built largely during the Tertiary period, probably increased somewhat in size in the course of the Quaternary period. Some, indeed, are thought to have had eruptions within the last few centuries. Except in Alaska and Mexico, however, the present is not a time of notable volcanic activity in western North America.

Animals of the Glacial Epoch

Mammals attain their modern state. — The Glacial epoch is so recent geologically that the animals of that time differ but little from those which exist to-day. Add to the mammals of to-day certain large forms which were common then, but have since been exterminated, and we have essentially the Quaternary fauna.

Migrations caused by glacial fluctuations. — Much more striking peculiarities are found when we compare, from the standpoint of their distribution, the animals of the present day with those of the Glacial epoch just preceding. Obviously the effect of the slow expansion of the ice sheets was to crowd all animals and plants away from the glaciated region,

and for the United States that meant in general southward. On the other hand, as the ice retreated during the milder times between glaciations, the same forms of life would be invited by the amelioration of conditions to press northward. In this way probably several backward and forward migrations were induced.

Southward advance of Arctic life. — In the strictly glacial times musk-oxen, such as now live in the Arctic regions, came as far south as Kentucky, and herds of reindeer ranged over the treeless hills of France. Elephants, such as the mammoth

FIG. 478. — The American mastodon. (Painted by Gleeson, in the *U.S. Nat. Mus.*)

and the mastodon (Fig. 478), and rhinoceroses, both covered with long, woolly hair, were among these Arctic types. Even their bodies with flesh and hide intact have been found preserved in the frozen gravels of certain Siberian rivers.

Southern forms come north. — During the genial intervals in which the glaciers disappeared, many southern animals

lived farther north than now. In Europe, hyenas, lions, hippopotami, and other African mammals reached England and Belgium. In the United States, at some such time, sloths and armadillos, related to South American types, frequented the southern states, coming as far north as Pennsylvania; while horses were abundant in Alaska, along with buffaloes (bisons) and elephants.

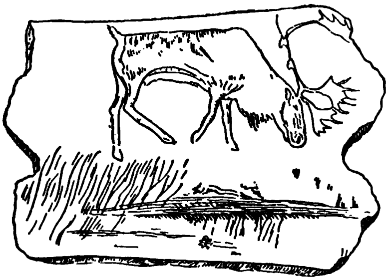

FIG. 479. — Drawing of a reindeer on a piece of bone, from a cave in southern Europe. (*U.S. Nat. Mus.*)

First appearance of man. — In the caves of France and some other parts of Europe, human bones and implements have been dug from beneath the hard layers of lime carbonate which incrust the floors of caves generally. With them are mingled the bones of the mammoth, reindeer, hyena, and hippopotamus, none of which have lived in central Europe in historic times, but which were plentiful there during the Glacial or Interglacial epochs. Doubtless these earliest human beings of which we have knowledge lived in the caves, and brought thither the bones of these animals, which they had killed with the rude stone-tipped spears and arrows now found with their skeletons. They have even left us fairly correct pictures of the reindeer, mammoth, bison, and other animals of this time, drawn on ivory and slate. It is uncertain whether man had reached America as early as the last glacial advance, for neither human bones nor implements have been found with

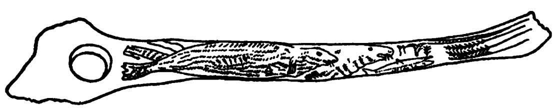

FIG. 480. — Seals carved on a piece of bone found in southern France. (*U.S. Nat. Mus.*)
Are seals found in that region to-day?

remains of the extinct animals of the glacial times. There is, however, no proof that he was not then on the scene.

The Recent Epoch

Little change since the glaciers passed away. — By the departure of the last ice sheet northern North America was left in very much its present condition. Streams have cut small valleys in the glacial drift, many lakes have been filled by the accumulation of silt and vegetable matter, and some have been drained; but aside from such minor changes the aspect given the land by the glaciers has been preserved through the few thousands of years which have elapsed since the ice retreated.

The Champlain submergence. — About the shores of Lakes Champlain and Ontario marine shells and the bones of whales have been discovered in beds of clay high above the present lakes. In order that the sea should have extended in so far, the land must have been several hundred feet lower than now. At this time the salt water probably spread up the Hudson River to Lake Champlain, and also up many other valleys in the East. That changes of level are still in progress is known from the fact that old beaches all along the Great Lakes are no longer level, as of course they must have been when made. In general, they are now higher on the north and northeast and are tilted southwestward. Those of Lake Superior gradually sink from an elevation of four hundred feet at the east end of the lake to lake level and even pass beneath the water before reaching Duluth.

Other slight risings and sinkings of the land have been in progress recently in many parts of the world. Indeed, there is scarcely a coast anywhere which does not reveal either raised beaches and sea-cut cliffs, or else drowned valleys and archipelagos. The former are conspicuous at many points in California and Alaska, while the latter are especially characteristic of the Atlantic coast of Maine and Britain.

Final readjustments in the living world. — Since the last retreat of the ice, only slight changes have been wrought in the living world. The animals and plants we have to-day are similar to those of the Glacial epoch. True, certain species have migrated from one region to another. Thus the reindeer has moved north to Lapland and Siberia. Such animals as the mammoth and the cave bear have become extinct. Few, if any, newer types, however, have appeared.

The event of chief importance, not only to us as human beings, but from a purely geological viewpoint, was the rapid spread and advancement of the races of men. Long before the dawn of historic times man had pushed outward from the place of his origin (itself yet unknown) and had colonized all the larger lands, and eventually even such remote islands as New Zealand and Hawaii, whither no other mammal except bats had ever gone. So long ago were the principal migrations made that the inhabitants of different continents have become distinct races through long isolation. Some of these races have since made comparatively little progress, while others have increased and developed with astonishing rapidity.

The geologic effects of human activities. — Probably no other land animal, certainly no other mammal, has equaled the human species in its effect upon the earth and its many living things. By digging canals he has connected seas and lakes hitherto separated. By cutting down the forests he has exposed to rain and wind the soils formerly held firmly upon the hills. Clear streams have thus become muddy, and permanent streams intermittent, while springs have disappeared and shifting sands have buried plains once fertile.

In an even more striking way man has produced changes in the animal and plant world. Certain kinds he has protected and domesticated, so that they have become abundant in many countries. Others he has hunted almost or quite to extinction. Among the former are the cat, dog, and cattle; while the auk, the passenger pigeon, and the bison may serve as examples of the latter. A full list of either would be long.

Some he has relegated to remote regions; thus the wild turkey was formerly common throughout eastern United States, but is now to be seen only in certain mountainous portions of the southern states. Still others he has transported all over the world; for example, the brown rat, originally a native of northwestern Europe, is now found in every continent and island in the habitable zones. In more recent times man has even been instrumental in producing entirely new varieties of animals, and especially of plants, by the method of controlled breeding, which is now so successfully practiced.

These are but a few examples of the many changes of which the human races have been the cause; but they are enough to show how very important the geologic and biologic influence of this highest of the mammals has become.

Questions

1. In the shape of the edge of the last ice sheet, what evidence is there of the former existence of a large valley where Lake Michigan now lies?

2. Part of this valley is now below sea level. To what extent do rivers erode their valleys below sea level? What other factors may have been important here?

3. In Indiana and Illinois the large bowlders in the drift are chiefly igneous and metamorphic rocks, such as granite, gneiss, gabbro, and quartzite, while bowlders of the sandstone and limestone which underlie the drift are less common. Why should this be true?

4. Have the uplands of Figure 477 been glaciated? The evidence?

5. At a point on the edge of the Wasatch Mountains in Utah a glacial moraine has been found dislocated, as shown in Figure 481. What events are indicated?

6. In northeastern California trees have been found associated with a bed of fine volcanic ash in the relations shown in Figure 482. What inferences may be drawn from this?

7. Why should the skeletons of mastodons and other large animals of the Glacial epoch be found in peat bogs?

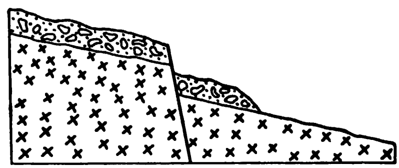

Fig. 481. — Dislocated terminal moraine.

8. Elephants are at present confined to the tropical region. Do the bones of elephants in Alaska and northern Siberia therefore indicate a tropical climate there in recent times?

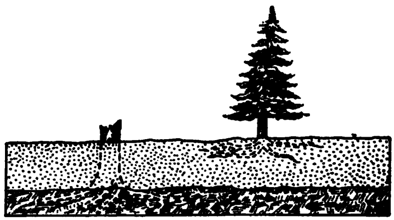

FIG. 482. — Relations of trees to a bed of volcanic ash near Lassen Peak, California.

9. Of the caves with relations as indicated in Figures 483 and 484, which affords the better evidence of the Glacial age of the human species, and why?

10. Applying the principles already learned from the past history of animals, how can you account for the fact that the Australian race of man has made less advancement than any other?

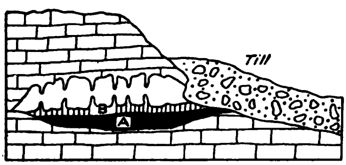

FIG. 483. — Section of a cave in limestone, showing earth (*A*) containing bones of men and extinct mammals, overlain by a crust of stalagmite (*B*), and the mouth of the cave closed by a deposit of till.

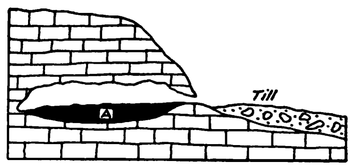

FIG. 484. — Section of a cave in limestone, the floor of which is covered with earth (*A*) containing human bones and implements.

11. In California the Quaternary glaciers were abundant on mountains eight to ten thousand feet high, while in Nevada the only peaks which had even small glaciers were more than eleven thousand feet high. Why should there be this contrast?

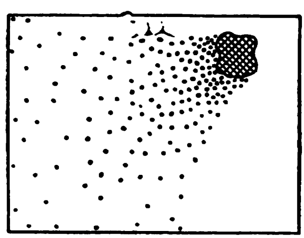

FIG. 485. — Map of the distribution of bowlders scraped off from an outcrop of igneous rock by a glacier.

12. In a locality in England bowlders derived from a small volcanic plug of peculiar rock are found distributed in the glacial drift as shown in Figure 485. Explain the fan-shaped distribution.

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